PROGRESS IN RESEARCH

April 1, 1992 - March 31, 1993

The reaction $^{12}\text{C}(d, ^2\text{He}) ^{12}\text{B}$ is studied in two proton correlation measurements with the proton spectrometer.

CYCLOTRON INSTITUTE
TEXAS A&M UNIVERSITY
COLLEGE STATION, TEXAS

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PROGRESS IN RESEARCH

APRIL 1, 1992 - MARCH 31, 1993

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July 1993

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INTRODUCTION

April 1992 - March 1993

This Institute annual report for the period 1 April 1992 - 31 March 1993 covers a period which has seen the initial runs of three new spectrometers which constitute a major portion of the new detection capabilities developed for this facility. These devices are the Proton Spectrometer (PSP) (data from which are shown on the cover of this document), the Mass Achromat Recoil Mass Spectrometer (MARS), and the Multipole Dipole Multipole (MDM) Particle Spectrometer. These devices are now available to pursue the studies of Gamow Teller states, reactions of astrophysical interest, and giant resonance studies for which they were constructed, as well as for other experiments. A beam analysis system which will deliver high resolution beams to the MDM spectrometer is currently under construction. With the completion of these spectrometer projects, the facility emphasis is now focused on the development of the full capabilities of the K500 cyclotron and on the research program.

During the report period, the ECR-K500 cyclotron combination operated 5,849 hours. The beam was actually on target 39% of this time, reflecting the large amount of time devoted to development, tuning, and optics of new beams -- notably ^2H to 70 AMeV, $^{63}\text{Cu}^{21+}$ to 40 AMeV and $^{129}\text{Xe}^{23+}$ to 12.5 AMeV.

Studies of nuclear dynamics and nuclear thermodynamics using the neutron ball have come to fruition during this period as indicated in Section I of the report. The CsI ball, which will complete our 4π charged particle detection system and will later see use with the neutron ball, will soon be completed.

In nuclear structure, a critical re-evaluation of the available data on the giant monopole resonance has indicated that the incompressibility is not specified to a range smaller than 200-350 MeV by those data. New systematic experiments using the MDM spectrometer are now underway. In the summer of 1992 the MEGA collaboration obtained the first data on the $\mu \rightarrow e\gamma$ decay rate and determination of the Michel parameter in normal μ decay. Experiments here with the Livermore e^+e^- spectrometer appear to confirm the existence of monoenergetic pair peaks even for relatively low $Z_{\text{projectile}} - Z_{\text{target}}$ combinations. Studies of the $(\alpha, 2\alpha)$ knockout reaction indicate that this reaction may prove to be a valuable tool for determination of

reaction rates of astrophysical interest as had been theoretically predicted.

Theoretical work reported in this document ranges from nuclear structure calculations using the IBM-2 model to calculations of kaon production and the in-medium properties of the rho and phi mesons, the latter as a probe of the QCD phase transition. Nuclear dynamics and exotic shapes and fragmentation modes of hot nuclei are also addressed.

In atomic physics, new measurements of x-ray emission from highly ionized ions, of molecular dissociation and of surface interactions are reported.

Noteworthy also in this year's report are the addition of Assistant Professor Sherry Yennello to the Nuclear Chemistry faculty and the progress toward development of a SEE radiation facility for study of radiation effects on space station components.

During the report period, 21 graduate students, 20 undergraduate students, and 14 post doctoral fellows have carried out research projects with Institute staff. Institute scientists have continued their outside collaborations in MEGA (LAMPF) and STAR (RHIC) during this report period, and have joined a new collaboration at Fermilab.

The research described in this report is funded primarily by the Department of Energy under grants DE-FG05-86ER40256 (nuclear) and DE-FG05-84ER13262 (atomic); by the National Science Foundation under grants PHY-8907986 and PHY-9001886 (theory); and by The Robert A. Welch Foundation under grants A-330, A-355, A-558, A-692, A-972, A-1082, A-1110, and A-1159. Operation of the facility is also supported by the University. The Texas A&M MEGA collaboration is supported under grant DE-FG05-87ER40310. Research in the STAR collaboration is supported under grant DE-AS05-85ER40207. The LAMPF few nucleon studies have been funded under grant DE-FG05-88ER40399. The MDM spectrometer and the analysis system are also funded by DOE under grant DE-FG05-86ER40256.

Some of the data and conclusions presented in this report are based upon preliminary analyses of the experiments. Until this research is published, it should not be cited without express consent of the investigators involved.

J. B. Natowitz
July 1993

HEAVY ION REACTIONS

Neutron Multiplicity Systematics and Energy Deposition in Reactions induced by 30 AMeV ^{14}N , ^{20}Ne , and ^{63}Cu

J. Boger, T. Botting, L. Cooke, B. Hurst, D. O'Kelly, R. P. Schmitt, and W. Turmel

For the past several years, measurements of fission fragment folding angles and evaporation residue (ER) recoil velocities have been used to extract information about the average linear momentum transfer in heavy ion reactions. (See for example Refs. 1 and 2 and references therein.) Such measurements, however, suffer from a number of difficulties. The first of these is that the position of the heavy fragment detector kinematically selects events within a restricted range of transferred momenta. Detectors placed at small angles with respect to the beam, for example, are sensitive to events with more complete momentum transfer and vice versa. The second difficulty is that the folding angle distributions are broadened by post-fission particle emission and the distribution of masses in fission. A similar difficulty is encountered with the detection of the ER's in that their velocities and positions are also affected by the emission of particles *en route* to the detector. All these factors limit the accuracy of the measured result.

It has been shown in Ref. 3, on the other hand, that the neutron multiplicity distribution $[P(M_n)]$ is sensitive to the excitation energy as well as the transferred linear momentum. The measurement of these distributions with a 4π neutron multiplicity detector is therefore expected to provide a more general probe of the violence of the collision between target and projectile without the limitations described above. We have, therefore, performed experiments that simultaneously test the systematics of linear momentum transfer and the extent to which the 4π neutron multiplicity detector may be used as an impact parameter filter.

Beams of 30 AMeV ^{14}N , ^{20}Ne , and ^{63}Cu provided by the K500 cyclotron have been used to measure the inclusive neutron multiplicity

distributions with targets that range in mass from ^{12}C to ^{238}U . The experiments were performed with the neutron ball⁴ in a self-triggered mode. Typical beam intensities ranged from ≈ 50 -100 particle pA.

Figure 1. Neutron multiplicity distributions corrected for background and pileup histograms, but not for detector efficiency. The beam is 30 AMeV ^{20}Ne and the targets are indicated in the figure. The smooth curves are fits to the data.

In Fig. 1 we present a number of selected multiplicity distributions corrected for background and pileup, but not for detector efficiency. The histograms are the experimental data, and the smooth curves are fits to the data, which will be discussed shortly. The projectile is ^{14}N and the targets are indicated in the figure. Similar multiplicity distributions were obtained for ^{20}Ne and ^{63}Cu projectiles.

For the heavier targets (beginning with ^{96}Mo), one observes an approximately exponential distribution of events for low multiplicities, and a broad, nearly Gaussian distribution for the higher multiplicities. This is not observed for the lighter

targets (for example ^{58}Ni), which show only the former component. The exponential component is identified with peripheral collisions between target and projectile, and the Gaussian component with the more central collisions. For the ^{14}N data, we have performed fits to the data for each projectile/target combination using the form

$$I_n = A \exp(-a_1 n) + B \exp[-a_2(n - n_0)^2], \quad (1)$$

where I_n is the intensity for events with multiplicity n . Accordingly, the neutron multiplicity distributions for the central collisions were characterized by their most probable value n_0 and their widths (or standard deviations).

Fits to the ^{14}N reactions are shown by the smooth curves in Fig. 1. We find rather good agreement between the data and the assumed functional form in all cases. Results of this analysis are listed in Table I. For the reactions with ^{20}Ne the same fitting procedure was used, although in a few cases a Gaussian fit was done to the high multiplicity component alone. In order to estimate the average efficiency of the neutron ball, one must take into consideration the kinematics of each target/projectile combination used in this experiment (as recoil velocities for the fused components will vary) and the energy distribution of neutrons (a function of the emitter temperature) in order to model the response of the detector. This is done using a very highly modified version of the code DENIS.⁵

For the average source velocity, the recoil velocity of the fused component was determined from the systematics in Ref. 2 for incomplete linear momentum transfer. Inclusion of the emitter temperature provides the Monte Carlo simulation with a way to generate a neutron energy weighted efficiency. Temperatures used in these calculations of the detector efficiencies were derived from the neutron energy spectra generated by the statistical model code CASCADE⁶ and are therefore averaged

over the de-excitation chain. Average detector efficiencies for each reaction are listed in Table I in the row labeled ϵ . Dividing the values of n_0 by ϵ gives the average neutron multiplicity corrected for the detector response ($\langle m \rangle$).

Figure 2. Experimentally derived average neutron multiplicities (solid circles) compared with statistical model calculations (open circles) for the ^{14}N -induced (top) and ^{20}Ne (bottom) reactions. Solid lines that connect the data are to guide the eye.

The statistical model code CASCADE has been used to calculate the average neutron multiplicities for the reactions listed in Table I. The linear momentum transferred to the fused component in these reactions is on the order of $\approx 74(\pm 12)\%$.² We have therefore used the simple reaction model which assumes that $\approx 74\%$ of the projectile mass and charge have fused with the target, while the other 26% of the projectile

is emitted at 0° with the beam velocity. This means for purposes of calculating average multiplicities with CASCADE, the following projectiles have been used in the calculations: ^{10}B and ^{15}N .

Figure 2 shows a comparison between the average neutron multiplicities calculated with the statistical model (open circles) and the experimentally derived multiplicities (solid circles) for ^{14}N and ^{20}Ne . Lines between the points serve to guide the eye. In Fig. 2, one notes that the calculated average neutron multiplicities are systematically high with respect to the experimental values. This tendency needs to be closely examined as it relates to the systematics of incomplete fusion as derived from fission fragment folding angles and ER recoil velocities. The uncertainties in the values of n_0 from fits to the data have been estimated by taking the differences between the fitted values (listed in Table I) and the values derived by taking weighted averages over symmetric intervals about the high multiplicity peaks.

Uncertainties in the statistical model calculations of CASCADE have been estimated from the experimental dispersions in the linear momentum transfer. From Ref. 2, this is typically about $\pm 12\%$ of the average transferred momentum. This means for the reactions studied here as little as 62% and as much as 86% of the incident linear momentum may have been transferred to the composite nucleus. For selected targets ^{100}Mo , ^{124}Sn , and ^{154}Sm , average neutron multiplicities were calculated for these upper and lower limits. Results are indicated by the error bars on the open points in Fig. 2.

Note that the calculated and measured multiplicities in the majority of cases lie outside their mutual calculational and experimental uncertainties for both the ^{14}N - and ^{20}Ne -induced reactions. This suggests at least two possibilities: (1) the statistical model overestimates the average number of neutrons emitted during a cascade, or (2) the amount of linear momentum transferred to the composite system is overestimated. It is also possible that the observed

overestimation is the effect of their combined result. This possibility is being currently investigated.

It is also important to note, however, that on a relative basis the data and calculated values agree quite well: neutron-rich nuclei give relatively large multiplicities and vice versa. This observation demonstrates that the decay of those nuclei that generate large numbers of neutrons is under statistical control. This is significant in that the neutron multiplicity distribution may be used as an impact parameter filter to separate the central and peripheral reaction processes involved in charged particle production, their energy spectra, and their angular distributions.

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Table I. List of targets and projectiles, results from fitting analysis, and detector efficiencies for each target/projectile combination.

	^{96}Mo	^{100}Mo	^{nat}Ag	^{116}Sn	^{120}Sn	^{124}Sn	^{144}Sm	^{150}Sm	^{154}Sm	^{174}Yb	^{197}Au	^{208}Pb	^{232}Th	^{238}U
Proj.	^{14}N													
n_0	5.45	6.51	6.58	-	7.48	8.82		-	10.21	10.70	12.82	13.44	15.81	16.12
σ	1.94	2.57	2.27	-	2.72	2.76		-	2.77	3.26	2.66	3.97	5.11	4.03
ϵ	0.776	0.774	0.779	-	0.784	0.784	0.798	-	0.800	0.788	0.804	0.805	0.810	0.807
$\langle m_n \rangle$	7.02	8.41	8.45	-	9.54	11.25	8.62	-	12.76	13.57	15.95	16.70	19.52	19.98
Proj.	^{20}Ne													
n_0	5.13	7.50	5.53	6.64	8.43	9.48	7.41	9.96	11.65	12.16	14.12	16.81	17.92	18.71
σ	2.39	2.33	2.93	2.70	2.82	3.23	2.81	2.64	3.71	4.00	4.31	4.46	4.61	4.73
ϵ	0.745	0.747	0.758	0.758	0.760	0.765	0.773	0.773	0.775	0.782	0.788	0.786	0.793	0.794
$\langle m_n \rangle$	6.89	10.04	7.30	8.76	11.09	12.39	9.59	12.93	15.03	15.54	17.92	21.39	22.60	23.56

Excitation Energy Partitioning in the Reaction $^{20}\text{Ne} + ^{208}\text{Pb}$ at 30 AMeV

B. Hurst, J. Boger, T. Botting, L. Cooke, D. O'Kelly, W. Turmel, and R. P. Schmitt

We have recently performed an experiment to study projectile-like fragments and neutrons produced in the reaction 30 AMeV $^{20}\text{Ne} + ^{208}\text{Pb}$. This particular system was selected to see if the neutron multiplicity distributions could shed some light on the origin of certain continuum structures reported in a variety of inelastic scattering experiments involving both low and intermediate energy heavy ions.¹ While these structures have sometimes been cited as evidence for multi-phonon excitations of giant resonances (GR) at high excitation energies, they have also been attributed to various sequential decay processes.²

The experiment used a self supporting 1 mg/cm² ^{208}Pb target. Measurements of the kinetic energy and angular distributions of the various fragments produced were made with an array of ΔE -E silicon detectors. The reaction was carried out in the scattering chamber of the neutron ball. The measurements were performed with the most forward wedges of the neutron ball (which subtend $\pm 20^\circ$) removed to facilitate the placement of particle detectors at small angles and also to insure that neutrons emitted from the PLF will have a small contribution to the total neutron multiplicity distributions. (i.e., The neutrons are strongly forward focused and so they are not detected by the neutron ball.) The total neutron multiplicity distribution should reflect the excitation energy deposited in the target. Projectile-like fragments (PLF) were detected using two triple-element, charged particle telescopes. Both PLF telescopes consisted of one 300 and two 1000 μm thick surface barrier transmission detectors collimated to 28.3mm². These two telescopes were placed near the grazing angle ($\theta_{\text{lab}} = 10^\circ$) at a distance of 35 and 11 cm from the target. In addition to the two PLF detectors, six more two-element charged particle

telescopes were included to gather angular distribution information on intermediate mass fragments (IMF) and fission fragments (FF). These six telescopes covered an angular range of 30° to 150° degrees (30° , 50° , 60° , 120° , 130° , and 150°).

Energy signals were recorded from each detector of the telescopes. The timing was determined by the first element. An event was triggered by the logical OR of the of particle telescope timing signals. The relative timing between each telescope was also recorded for each event to allow analysis of possible particle particle coincidences.

Since low neutron multiplicities are expected for the more peripheral reactions, the contribution due to background must be kept to a minimum. One way this can be accomplished is by varying the counting and background gate widths. In-beam measurements were made to determine an optimum gate width of 40 μsec . With this gate width the average neutron background was found to be about 0.5 neutrons per event. For a 40 μsec gate width, Monte-Carlo calculations using a modified version of the code DENIS³ predicts an overall efficiency of 70-75% for ^{252}Cf neutrons. The analysis of the data is currently in progress.

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Reaction Dynamics in the Formation and the Decay of Hot Nuclei in $^{63}\text{Cu} + \text{Au}$ at 35 AMeV

R.Wada, K. Hagel, R. Tezkratt, G.X. Dai, Y. Lou, D. Utley,
B. Xiao, J. Li, N. Mdeiwah and J. B. Natowitz

How hot a nucleus can one make in heavy ion reactions? When the incident energy of the projectile increases, the nucleons behave more and more like free nucleons and some of them emerge leaving little energy in the composite system. The distribution of the linear momentum transfer has been studied in $\text{Ar} + \text{Au}, \text{Th}$ reactions from 27 AMeV to 77 AMeV¹ and leads to observations of the sharp decrease in cross section for fission events which have a folding angle near that expected for central collisions. This was interpreted as a limit to the excitation energy of the compound nucleus at 600-700 MeV. On the other hand the average neutron multiplicity, measured in the same experiment, steadily increases with increasing incident energy, at least from 27 AMeV to 44 AMeV. This may suggest that the hot composite system with high neutron multiplicity decays by channels other than fission. In fact fission decay channels are significantly hindered at the high excitation energies because of the slow deformation time of nuclear matter.^{2,3} This may change the decay processes of hot nuclei drastically.

In order to pursue this problem different decay channels were observed in coincidence with the associated neutron multiplicity in $^{63}\text{Cu} + ^{197}\text{Au}$ at 35 AMeV. The experiment was performed at the Texas A&M K-500 superconducting cyclotron facility. The ^{63}Cu beam was incident on an Au target with an areal density of $0.45\text{mg}/\text{cm}^2$. Neutrons were detected by the Texas A&M 4π neutron ball. Heavy particles such as evaporation residues and fission fragments were detected by a large area Si detector ($5\text{cm} \times 5\text{cm}$) at $\theta = 6^\circ$ at a distance of 65cm from the target. Mass and velocity are calculated from the time of flight and the observed energy. A gamma flash signal from the neutron ball was used as a start signal for the time of flight. The system was calibrated with ^{252}Cf fission fragments. Projectile-like

fragments were detected at $\theta = -6^\circ$ by a telescope with a large area Si strip detector ($4\text{cm} \times 6\text{cm}$, 7 strips) backed by 5mm CsI crystal detector. Intermediate mass fragments were detected by four Si telescopes at 15° , 30° , 45° , 60° , and two Gas-ionization chamber-Si telescopes at 80° and 120° . Two monitor Si detectors ($\Delta\Omega = 5\mu\text{sr}$, 2mm thick) were set at $\theta = \pm 2^\circ$ to normalize all measured cross sections to the Rutherford scattering. The cross sections presented below are given in absolute units. In this report we focus on the heavy fragments measured at $\theta = 6^\circ$ in coincidence with the neutron multiplicity.

Figure 1. Inclusive neutron multiplicity distribution. No background and efficiency corrections have been made.

In Figure 1 the observed neutron multiplicity is shown. No background and efficiency correction has been made for this figure. The average background multiplicity was 2.1 over all runs. The efficiency of the ball is about 75% for the neutrons isotropically evaporated from a slow moving source. The distribution shows clearly two components, one peaked at the lower multiplicity and the other with a peak at $M_n \approx 26$. Apparently the former corresponds

to the peripheral collisions and the latter to the more central collisions.

Cu+Au at 35 AMeV

Figure 2. Upper: Average neutron multiplicity vs. fragment velocity in coincidence with fragments of different mass ranges indicated in the figure. Background neutron multiplicity has been corrected. Lower: Measured mass vs. velocity distribution at 6° . Contour levels are 1.0, 10.0, 20.0, 30.0... mb/sr/(cm/ns).

In Figure 2 a contour plot of the mass vs. velocity for the fragments detected at $\theta = 6^\circ$ is shown with the accompanying average neutron multiplicity. The neutron multiplicity is given for two mass regions. The multiplicities are corrected for background but not for the neutron ball efficiency. Fragments with mass $A \sim 150$ and $V = 0.5$ - 1.5 cm/ns are observed. These heavy fragments are associated with a high neutron multiplicity and the multiplicity increases with increasing velocity. The fragments with $50 \leq A \leq 100$ also show similar neutron multiplicities and trends with a velocity offset of about 1-1.5 cm/ns. This high neutron multiplicity indicates that these lighter fragments may originate from similar reactions to those leading to the heavier fragments. In fact the above observations are consistent with a picture of an incomplete fusion reaction followed by either evaporative decay or fission-evaporation decays. The former scenario leads to the heavy residues and the latter to the lighter fission fragments. The heavy fragment velocities of

0.5-1.5 cm/ns correspond to reactions with 40-75% linear momentum transfer if these originate from an incomplete fusion-evaporation process. For the fission decay one of the fragments has to be emitted at a forward angle in order to be detected at $\theta = 6^\circ$. The 1-1.5 cm/ns offset corresponds to the Coulomb velocity of the forward emitted fragment added to the velocity of the parent nucleus.

Figure 3. Upper: Primary compound nucleus mass distribution vs impact parameter calculated by EUGENE. Lower: Angular momentum and excitation energy of the primary compound nucleus in upper figure.

The experimental results have been compared with model simulations. In order to treat entrance channel effects, such as preequilibrium particle emission, the first part of the code EUGENE is used.⁴ In this part of the program the preequilibrium nucleon emission for a given impact parameter is treated by following nucleon-nucleon collisions in the overlap region of the projectile and the target. The rest of the projectile is treated as a spectator and flies

away with little energy dissipation. The properties of the primary excited nuclei are generated for the impact parameter range of 0-12fm. The contour plots of mass vs. impact parameter and excitation energy vs. angular momentum for the primary nuclei are shown in Figure 3. The primary mass of the compound nucleus is $A \sim 250$ for the central collisions and $A \sim 200$ for the peripheral collisions. The calculated excitation energies for the primary nuclei reach 1.5 GeV.

These primary nuclei are allowed to decay statistically, using the code GEMINI.⁵ In GEMINI, thermal equilibration is assumed and all particles are emitted sequentially. The light particle emissions are treated by the Hauser-Feshbach formalism, and the emission of fragments with $Z \geq 3$ is treated by the transition state formalism. The relative angular momenta and spins are properly treated.

Another important ingredient is added for the sequential decay process. Recently Hilscher *et al.* have reported that the time scale of the scission of two fission fragments is of the order of 10^{-20} sec, which is much slower than that of the evaporation at the excitation energy of 2-3 MeV/nucleon.² This is interpreted as the dynamical delay of a fission decay, because the scission time is governed by the nuclear deformation time. In measurements of pre and post scission particle emission in the reaction $^{136}\text{Xe} + ^{48}\text{Ti}$ at 18.5 AMeV, we have found that the delay time depends on the asymmetry at the scission point and decreases with increasing asymmetry.³ While this result may include significant contributions from deep inelastic processes, we explore here its possibilities for the present system. Our result for that system is given by an approximate expression

$$\tau_{\text{scission}} = \left(\frac{A1}{A2} \right)^{\gamma_0} \tau_0 \quad (1)$$

where $\tau_0 = 1.0 \times 10^{-20}$ sec. Here $A1$ and $A2$ are the mass of the two fragments and $A1 \leq A2$ is assumed. From the above experiment $\gamma_0=1.5$ is extracted for a constant inverse level density parameter $K=10$ and $\gamma_0=2$ for the temperature

dependent level density parameter. In the following simulations, $\gamma_0 = 0, 1, 2$ is used to see the dependence of the results on the different delays. In the case of the $\gamma_0=0$ this delay was applied only for $A1 \geq 30$ and a linear increase of the delay between $A=5-30$ is assumed. For the different delays the calculated scission time for $A = 230$ is shown in Fig.4. In the following $\gamma_0=0$ is called constant fission delay (CFD) and $\gamma_0=2$ and 1 are called mass dependent delay (MDD) A and B, respectively.

Figure 4. Fission dynamic delays used for the calculation. See details in text.

The calculated neutron multiplicity distributions are rather independent of the dynamical delay constant γ_0 . The generated neutron multiplicity distribution is shown by the solid histogram in the top of Fig.5. In order to compare with the experimental result each neutron is filtered by the neutron ball efficiency. The filtered distribution is shown by a dashed histogram in the figure. The calculated distribution shows a peak at $M_n \approx 17$, which is much lower than that of the experiment ($M_n \approx 26$). At the bottom the neutron multiplicity distributions are shown for different ranges of the impact parameter. The results are all filtered. For most central collisions the distribution shows a gaussian shape with a peak at $M_n \approx 28$ and that for the peripheral collisions is at $M_n = 16.5$.

Figure 5. Upper: Calculated neutron multiplicity (solid line) by EUGENE-GEMINI calculation. Dotted line indicates multiplicity after experimental filter. Lower: Calculated filtered neutron multiplicity for different impact parameter ranges indicated in figure.

In Figures 6-8 the results of the calculated velocity vs. mass distribution are shown for the different fission delays. No experimental angle selection is made in these figures. The associated neutron multiplicity is also shown in the upper part of each figure. For the case without delay (Figure 6), very little cross section for the fragments with $A=100-150$ and velocity $V \geq 0.5$ cm/ns is obtained. These fragments with $V \leq 0.5$ cm/ns have an average neutron multiplicity $M_n \leq 20$. One can see a large population for mass $A \sim 50-120$. This indicates that essentially all the hot primary nuclei undergo fission decay. For a constant fission delay (CFD) a drastic difference is observed as seen in Figure 7. A large cross section of heavy fragments with $A=140-180$ and $V=0.5-2.0$ cm/ns is observed. Those fragments with $V \geq 1.0$ cm/ns have the average neutron multiplicity $M_n \geq 20$. For MDD B the results are almost identical to those of CFD. For MDD A (Figure 8) the calculated trends are similar to those for CFD, but the heavy fragments are slightly lighter, especially at the higher velocities, and the cross section is lower. More detailed comparisons with the

experimental results are underway.

Figure 6. Similar plots to Fig. 2 for the EUGENE-GEMINI calculation with no dynamic delay. No selection is made for fragment emission angle. Same contour levels are used as those in Fig. 2.

It has been pointed out that an incomplete deeply inelastic process can play an important role for the heavy ion reactions in this energy region.⁶ In order to simulate this process the code HICOL is used.⁷ HICOL is a program which calculates the two body trajectory between two heavy fragments with neck formation. Nucleons in both sides can be exchanged through this neck, generating the energy dissipation. In the left of Figure 9, the calculated results are shown. No preequilibrium emission is taken into account. From the top, the masses, excitation energies, angular momenta of both fragments and the scattering angle of the light fragment in the center of mass are plotted as a function of the impact parameter b . In this calculation the collision with $b \leq 4$ fm goes to a fusion reaction. In order to simulate the reaction on an event by event basis, this program was modified to a Monte Carlo version. The generated events are plotted in the right side of Figure 9. In the figure the excitation energy and angular momentum are given only for the fragment with smaller mass for clarity. The generated events were used as the input for GEMINI. Fusion events

are not treated here. In Figure 10 the calculated neutron multiplicity distribution is given by a solid histogram and the filtered one is shown by the dashed histogram. The peak value for the smaller impact parameter is $M_n \approx 30$, which is about 4 units higher than the experimental value. This may be caused by the fact that no preequilibrium emission was taken into account. The calculated mass distribution without the delay is given by a solid histogram in Figure 11. One can see two sharp peaks around $A \approx 60$ and 160, which are projectile and target residues from peripheral collisions. These disappear when an associate neutron multiplicity of $M_n \geq 10$ is required (dashed histogram).

Figure 7. Same plots as Fig. 6 in the case of dynamic delay of CFD in Fig. 4.

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Figure 8. Same plots as Fig. 6 in the case of the dynamic delay of MDD A in Fig. 4.

Figure 9. Calculated results of the program HICOL (left column) and those for the Monte Carlo version. From the top mass, excitation energy, angular momentum and scattering angle are plotted as a function of the impact parameter. In the right column excitation energy and angular momentum are given only for the lighter fragment.

Figure 10. Calculated neutron multiplicity for the program HOCOL-GEMINI. The filtered multiplicity is shown by a dashed line. No fission dynamic delay is assumed.

Figure 11. Calculated mass spectrum for HICOL-GEMINI with no dynamic delay. No selection for the emission angle of the fragment is made. Dashed line is indicated for those with the associate neutron multiplicity ≥ 10 .

The Fate of Compound Systems in Reactions of 40 AMeV Ar with Th or Au Targets

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Introduction

Beams from the K-500 superconducting cyclotron have been used in experiments with the neutron ball to explore the limits to excitation energy in compound nuclei formed in the reactions Ar + Th, Au, Mo and Ni with projectile energies of 35 AMeV and 40 AMeV.¹ Analysis of the data from the Th and Au runs is nearing completion. Selected results are presented here for the 40 AMeV Ar experiments.

Experiments with 44 AMeV Ar projectiles incident on Th and Au targets carried out by groups from GANIL and the Hahn Meitner Institute, were interpreted as suggesting an upper limit to the excitation energy of 600-800 MeV for this system.² Calculations completed here show the detector angle of 20° reported by the Berlin group may be too large to detect the majority of residues which might be produced from collisions central enough to induce excitation energies above 700 MeV, should such residues avoid fissioning.

In an experiment at 35 AMeV residues with mass greater than 150 u were found to have neutron

multiplicities similar to those found in fission. A follow up experiment with the capability of obtaining the light charged particle (LCP) energy spectra, LCP multiplicities and neutron multiplicities in coincidence with heavy residues and projectile like fragments at selected lab angles was completed.

Complementary experiments at 40 AMeV were carried out in the scattering chamber of the Neutron Ball. Light charged particle (LCP) telescopes consisting of ionization chambers backed by CsI/PMT detectors were positioned at 20° intervals in the reaction plane. Four 300 micron silicon strip detectors 6 cm × 5 cm each divided into three regions for angular resolution were placed in the forward direction: two at 45 cm and two at 68 cm from the target. The two detectors at 68 cm were backed by 0.5 cm CsI crystals for identification of the projectile like fragments. The residue detectors provided coverage from 3.4° to 12° from the beam. Mass determinations were made at 6° by time-of-flight measurements using a channel plate detector and a 900 sq. mm. silicon surface barrier detector

separated by a 125 cm flight path. Detector responses were determined using Cf-252 (alphas, fission fragments and neutrons), Am-241 (alphas), Gd-148 (alphas), and a Ta-181 beam degraded and scattered by gold and/or aluminum foils.

Table I. Summary for 40 AMeV Ar Beams on Gold and Thorium Targets

Target	Au		Th	
Average Values	Fission	Residue	Fission	Residue
<Mass>	82	142	103	164
<Lab Energy>	146	57	143	69
<N>	19.0 ±.5	19.7 ±.5	18.9 ±.3	21.0 ±.7

All values are average values. Neutron multiplicities are background corrected, but not efficiency corrected.

Summary of Results

Average values of the fission and residue characterizations are listed in Table I. Lab energies, average neutron multiplicities, the derived particle masses, linear momentum transfer (LMT) and excitation energies for 40 AMeV Ar incident on Th and Au targets are given for comparison. Mean fission fragment masses are roughly 60% of the mass of the residues in both cases. The average mass in the Au case is 20 amu less than the respective masses in the Th case, reflecting the lower mass of the target. An estimate of linear momentum transfer (LMT) based on the listed average values would lead to LMTs of 55% for the gold target and 65% for the thorium target. Systematics for a 40 AMeV projectile would suggest a slightly higher percent LMT in the range of 70%.³

The neutron numbers listed are corrected for background and efficiency. Efficiencies are with respect to the Cf-252 neutrons. Actual efficiencies may be somewhat lower for a moving hot neutron source. A fact that would lead to slightly higher neutron numbers.⁴

Estimates derived from the LMT values would

lead to excitation energies of 715 MeV for the gold case and 870 MeV for the thorium case. These values are mean values. As will be discussed later, excitation energies in excess of 1000 MeV are suggested in some events for the residues from the thorium target.

Figure 1. Contour plot of particle mass vs. lab velocity at 6° in the lab, 40 AMeV Ar + Au: Light particles and intermediate mass fragments are to the left, fission fragments peak near 100 amu, residues peak near 150.

Lab Velocity of the Particle

Contour plots for the detected particle lab velocity versus the particle mass are shown in Fig. 1 for the Au target and in Fig. 2 for the Th target. Particle masses are determined from the time-of-flight and the energy of the detected particle. Suitable corrections for pulse height defect in the energy⁵ and plasma delay in the timing have been made. In both plots residues, fission fragments and lighter particles are clearly recognizable. The detector was located at 6° from the beam.

In Fig. 1 light particles and projectile like fragments are seen at low mass, A less than 50. Fission fragments are found in the mass range from approximately 50 to 120. Residues are those events with mass greater than 120. The results for the Th target are given in Fig. 2. Here the three classes of events are still clearly separable. The yield of residues is noticeably less in this case illustrating the increase in fissionability of the compound system

formed with the Thorium target.

The data for the light particle velocities extend to beam velocity. The plots are truncated to focus attention on the heavier residues and fission fragments.

Figure 2. Contour plot of particle mass vs. lab velocity at 6° in the lab, 40 AMeV Ar+Th: Mass regions shift by 20 amu. the change in relative yields between fission fragments and residues is evident.

Mass spectra determined from the time-of-flight and kinetic energy of the particles are presented in Fig. 3 for the Au target and in Fig. 4 for the Th target. The relative number of events in the three regions may be seen in these figures. The low mass maximum (below 10 amu) also includes particles of higher mass which have penetrated the active region of the surface barrier detector. These higher energy particles deposit only a part of their total energy resulting in a low mass determination. Relative yields of the residues and the fission events will be discussed as a function of source velocity later.

Associated Neutrons

Average background corrected neutron multiplicities associated with the masses observed in Fig. 3 and Fig. 4 are presented in Figs. 5 and 6, respectively. The neutrons are not corrected for detector efficiency. The efficiency of the neutron detector for Cf-252 neutrons was 69.8%.

In these figures the mass bins of 10 amu were centered on the given points. The average neutron

Figure 3. Projection on the mass axis of the plots in Figure 1: the centroid of the fission fragments is 8°, that for the residues is 142.

multiplicity values for all particles in a given mass range are plotted.

Figure 4. Projection on the mass axis of the plots in Figure 2: the centroid of the fission fragments is 102, that for the residues is 164.

Immediately of interest is the observation that fission fragments and residues have similar neutron numbers with residues on the whole having only slightly higher values. Closer inspection of the data in the region of fission fragments for Th shows a decrease in detected neutron multiplicity with an increase in mass number. The neutron multiplicity for fission events decreases from 22 at mass 65 to 18 at mass 115. The multiplicity then rises with increasing mass to 155 then decreases with increasing mass.

Figure 5. Average neutron multiplicities in coincidence with particle mass. Error bars are the error estimates of the mean values. Ar + Au

Figure 6. Average neutron multiplicities in coincidence with particle mass. Error bars are the error estimates of the mean values. Ar + Th

Similar trends are seen for residues and fission fragments in the Ar + Au case.

The higher velocities and the higher associated neutron multiplicities with decreasing mass separately seen for each class of events would be consistent with the lighter mass products in both classes being produced in more central collisions (i.e. the lower the mass within each class, the smaller the impact parameter).

Relative Yields

Relative yields at 6° for fission fragments and residues as a function of source velocity are presented

Figure 7. Yield of fragments by source velocity: gold target, fission fragment source velocities are corrected for Coulomb repulsion assuming symmetric fission.

in Figure 7 and Figure 8. The source velocity of the residues is taken to be the lab velocity. The source velocity for the fission fragments is calculated by subtracting the fission fragment velocity determined using Viola systematics⁶ from the observed laboratory velocity. The source velocity for fission fragments is then the source velocity of the fissioning system. The residue yields in the Th case have been further separated into two mass ranges: masses 140 to 160 (RESLOA), and mass greater than 160 (RESHI). For the Ar + Th case the yields are dominated by fission at all source velocities. The vast majority of the fission fragments are associated with slower source velocities and thus are most likely formed in collisions with larger impact parameters. In the plot it is seen that residue cross section peaks at a source velocity near 0.9 cm/ns. When the low residue mass region is compared to the high residue mass region for the Th residues it is seen that the lower mass residues result from collisions with larger momentum transfers as indicated by a higher source velocity.

The plot for the Ar + Au case illustrate the larger relative yield of residue production for the lower mass target. Fission dominates for the slower sources interpreted to result from the most peripheral collisions as indicated by the low source velocities. Residue production begins to compete effectively by

Figure 8. Yield of fragments by source velocity: Thorium target; RESLOA, 140 to 160; RESHIA, above 160.

0.5 cm/ns and is favored over fission above 0.7 cm/ns.

While excitation energies of 700 MeV and 800 MeV for the Au target and the Th target are implied by the average LMT, collisions resulting in the mass transfer needed to achieve the source velocities in these figures are expected to result in excitation energies for the more central collisions in the range of 1000 MeV.

Conclusions

Similar neutron numbers prevent neutron multiplicities from distinguishing between reactions leading to fission or residue formation. Source velocities and trends in the neutron multiplicity suggest the residues (in the case of the Th target) result from the more central collisions with higher excitation energy. Within both fission and residue groups higher neutron multiplicities are associated with lower detected particle mass.

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Fission in the Reactions of $^{63}\text{Cu} + ^{100,92}\text{Mo}$ at 10, 17 and 25 AMeV and $^{20}\text{Ne} + ^{144,148,154}\text{Sm}$ at 20 AMeV

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To study hot excited nuclei with $A \approx 160$ having different proton to neutron ratios, we have analyzed the data on fission and light particle decay for the reactions $^{63}\text{Cu} + ^{92,100}\text{Mo}$ at bombarding energies of 10, 17, and 25 AMeV, and $^{20}\text{Ne} + ^{144,148,154}\text{Sm}$ at a bombarding energy of 20 AMeV. These were carried out at the K500 Cyclotron using the TAMU neutron ball.¹

To characterize the fission events based on the energies and the detected angles of the fragments we apply momentum conservation at the scission point. We assume the light particle evaporation is symmetric before and after the scission point, so that the velocities of the compound nucleus and the fission fragments will not change. Assuming the total mass is M_{tot} at the scission point, we can get the fission fragment masses m_1 and m_2 .

$$M1 = \frac{M_{tot} \times E2 \times \sin^2 \theta_2}{E1 \times \sin^2 \theta_1 + E2 \times \sin^2 \theta_2}$$

$$M2 = \frac{M_{tot} \times E1 \times \sin^2 \theta_1}{E1 \times \sin^2 \theta_1 + E2 \times \sin^2 \theta_2} \quad (1)$$

and the velocity of the compound nucleus at the scission point is

$$V_{cn} = \sqrt{\frac{2 \times E1 \times E2}{M_{tot} \times (E1 \times \sin^2 \theta_1 + E2 \times \sin^2 \theta_2)}} \times \sin(\theta_1 + \theta_2) \quad (2)$$

The Linear Momentum Transfer, ρ , is then:

$$\rho = \frac{M_A}{M_a} \times \frac{V_{cn}}{V_a - V_{cn}} \quad (3)$$

In Fig. 1(a) we show the Linear Momentum Transfer Distributions for the Cu + Mo cases for different fragment mass windows. Fig. 1(b) shows the same for the Ne + Sm cases.

Simulations¹ show that the widths of the LMT distributions are primarily due to light particle evaporation. This accounts for the spread to apparent $LM1 \approx 100\%$. For the 25 AMeV cases, the peak position is lower than expected since the experimental set up just covered the low LMT part of the distribution.

The total neutron multiplicities are determined using the neutron ball triggered by fission fragment detection. Excitation energies corresponding to the most probable LMT were calculated assuming 85% LMT for the 20 AMeV $^{20}\text{Ne} + ^{144,148,154}\text{Sm}$ and 100%, 90%, and 80% LMT for 10, 17, and 25 AMeV $^{63}\text{Cu} + ^{92,100}\text{Mo}$ reactions. Fig. 2 shows the total observed neutron multiplicities vs. neutron number in the compound nucleus for excitation energies near 300 MeV. The detected neutron multiplicity increases with the neutron number in the compound nucleus. Fig. 3 shows the total neutron multiplicity depends on the excitation energy for the Cu + Mo cases. While the multiplicities increase with energy, they do not increase sufficiently to account for all the excitation energy.

The light charge particle emission data are in the process of analysis.

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Figure 1. LMT plot for (a) $^{63}\text{Cu} + ^{92,100}\text{Mo}$ at 10, 17, and 25 AMeV. The different lines present the different mass windows. (b) the same for 20 AMeV $^{20}\text{Ne} + ^{144,148,154}\text{Sm}$ cases.

20 MeV/u $^{20}\text{Ne} + \text{Sm}$ or 10 MeV/u $^{63}\text{Cu} + \text{Mo}$

Figure 2. Total neutron multiplicities as a function of neutron number in different compound nuclei. The compound nucleus excitation energy is about 300 MeV.

10 17 and 25 MeV/u $^{63}\text{Cu} + \text{Mo}$

Figure 3. Total neutron multiplicities as a function of the excitation energy for the reactions $^{63}\text{Cu} + ^{92,100}\text{Mo}$ at bombarding energies of 10, 17, and 25 MeV/u.

Decay of Hot Nuclei in the Reaction $^{63}\text{Cu} + ^{63}\text{Cu}$ at 35 AMeV

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To study the systematics of the reaction mechanisms and decay properties of hot nuclei, a 35 AMeV ^{63}Cu beam from the Texas A&M K-500 superconducting cyclotron has been used to irradiate a Cu target. IMFs were detected by four Si+Si+CsI ($\Delta E_1 + \Delta E_2 + E$) telescopes sitting at 15° , 30° , 45° , 60° , and two gas-ionization chamber + Si telescopes at 80° and 120° . Residues and fragments were detected by a large Si detector ($5\text{cm} \times 5\text{cm}$) at $\theta = 6^\circ$ at a distance of 65 cm from the target. A telescope with a 7-strip Si detector ($4\text{cm} \times 6\text{cm}$) backed by a 5 mm thick CsI crystal at -6° was used to detect projectile-like fragments (PLFs) and also IMFs. Neutrons were detected by the Texas A&M 4π Neutron Ball. All the charged particles were detected in coincidence with the neutrons.

$\text{Cu}+\text{Cu}$ at 35 MeV/u

Figure 1. Neutron multiplicity distribution without background and efficiency correction.

The neutron multiplicity distribution is shown in Fig. 1 without background and neutron ball efficiency corrections. The average background is 2.1 neutrons

Figure 2. Scatter plot of energy vs time of flight of the residue detector.

over the entire run. The efficiency depends on the neutron energy. The $\pm 15^\circ$ opening of the ball causes the neutron detection efficiency of the ball to depend even more heavily on the velocity of the source in this case. All the neutron multiplicity data shown below are uncorrected for efficiency or background. Higher neutron multiplicity corresponds to more violent collisions. Fig. 2 shows the scatter plot of $E(\text{energy})$ vs $T(\text{time of flight})$ for the residue detector. Those events inside the window are the heaviest products detected at 6° . The straight dense line of events corresponds to PLFs, some of which punched through the detector. In Fig. 3 we show the neutron multiplicity distribution gated by the window in Fig. 2. The peak of the distribution is around 10 and this suggests that those heavy masses with slow velocities come from very violent collisions. The correlations between the average neutron

multiplicities and the fragment charges detected by telescopes at different angles are plotted in Fig. 4.

Figure 3. Neutron multiplicity distribution gated by the blob shown in Fig. 2.

The overall pattern is very similar to results for heavier systems.^{1,2} At $\theta = 4^\circ$ the first strip of the seven-strip Si detector is selected. One can easily notice that the fragment charge is strongly correlated with the neutron multiplicity, which indicates that the charge of PLFs, as well as the neutron multiplicity, can be used to gate impact parameter. The larger the angles, the less the neutron multiplicity depends on the fragment charge. At $\theta = 60^\circ$ all fragments have average neutron multiplicities of 10 to 11, which corresponds to the peak of the multiplicity distribution observed in Fig. 3. Thus one can conclude that the IMFs observed at large angles were produced from collisions similar to those which generated the heavy fragments. One should also note that the correlations between fragments and neutron multiplicities at larger angles indicate a slight increase of neutron number with increasing fragment mass.

Figure 4. Correlations between the average neutron multiplicities and the fragment charges detected by telescopes at different angles.

We are continuing to explore the deexcitation mechanism of the most violent collisions by extracting average multiplicities of fragments and particles as a function of neutron multiplicity.

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The Multifragmentation of $^{40}\text{Ca} + ^{40}\text{Ca}$

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We have continued the analysis of $^{40}\text{Ca} + ^{40}\text{Ca}$ for which some results have been reported previously.^{1,2} For angles larger than 20° , a new energy calibration of the AMPHORA detector has been accomplished by comparison to data for the 35 AMeV $^{40}\text{Ar} + ^{40}\text{Ca}$ system. The calibration of the detectors at angles less than 20° was accomplished by comparing data taken at the same time as the $^{40}\text{Ca} + ^{40}\text{Ca}$ experiment but using a Cu target to a 36 AMeV $^{40}\text{Ar} + ^{58}\text{Ni}$ run from GANIL.³ These new calibrations have enabled us to compare more of the experimental observables to theoretical model predictions. As before, all model calculations presented have been filtered through the experimental acceptance.

Multiplicity Distributions

In Figure 1 we present comparisons between experimental and calculated multiplicities and multiplicity distributions. The solid points represent the experimental data, the solid histograms show the results of the calculation of Sa and Gross,⁴ the dotted histograms are from the GEMINI⁵ calculation for $\ell_{crit} = 20\hbar$, and the dashed histograms are from the GEMINI calculation for $\ell_{crit} = 80\hbar$. In Figure 1a we show the proton multiplicities. We note that the proton multiplicity as given by the multifragmentation calculation almost exactly reproduces the experimental data. The GEMINI calculations show a slight overprediction, with the calculation for $\ell_{crit} = 80\hbar$ in slightly better agreement than the one for $\ell_{crit} = 20\hbar$. Figure 1b shows the α multiplicities. Both the multifragmentation calculation and the two GEMINI calculations underpredict the α particle multiplicity. Figure 1c shows that the multifragmentation calculation overpredicts the number of IMF's by about 1, whereas the two GEMINI

calculations both underpredict the number of detected IMF's. This was evident in our previous paper⁶ where it was observed that all GEMINI events had small values of the second moment of the Z-distribution, S_2 . In the multifragmentation calculation, on the other hand, all events have a large value of S_2 .

Figure 1. A comparison of multiplicities of various calculations to experiment. The solid points represent the data, the solid histograms represent the multifragmentation calculation, the dotted histograms represent the GEMINI calculation for $\ell = 20\hbar$, and the dashed histograms represent the GEMINI calculation for $\ell = 80\hbar$.

Figure 2. A comparison of the multifragmentation calculation protons to the experimental data for the AMPHORA angles as indicated.

Figure 3. A comparison of the multifragmentation calculation α particles to the experimental data for the AMPHORA angles as indicated.

Figure 4. A comparison of the $\ell = 80\hbar$ GEMINI calculation protons to the experimental data for the AMPHORA angles as indicated.

Figure 5. A comparison of the $\ell = 80\hbar$ GEMINI calculation alpha particles to the experimental data for the AMPHORA angles as indicated.

Figures 1d, and 1e show the relationship between proton and α multiplicities, respectively, and the IMF multiplicity. For the proton case in Figure 2d, we note a qualitative agreement for both the multifragmentation calculation and both GEMINI calculations. The relationship between the α -particle multiplicity and IMF multiplicity does not reproduce the experiment as could be expected from Figure 2b.

Energy Spectra

In Figure 2 we present a comparison of the experimental proton energy spectra to the predictions of the simultaneous multifragmentation of Sa and Gross.⁴ The input parameters are identical to the ones reported earlier.^{2,6} We observe very good agreement in the shapes of the spectra at all angles, and the intensity is also reproduced between the angles of 20° and 90°. A comparison of the α particle spectra in Figure 3 leads to essentially the same conclusions, however there is a low energy experimental component in the experimental spectra which the model does not reproduce. It is this missing component that causes the experimental α particle multiplicity distribution in Figure 1b to deviate from the calculated distributions.

In Figure 4 we present the proton energy spectra produced by GEMINI overlayed on the experimental energy spectra. We notice that the shapes of the calculated proton energy spectra are very close to those of the experiment although the angular distribution is obviously different. Figure 5 shows a comparison between the α particle energy spectra as given by GEMINI and the experiment. The shapes of the alpha particle energy spectra given by GEMINI do not agree as well as do those for the protons.

These two comparisons indicate that the protons probably do not shed much light on the process of multifragmentation. This is because the spectral shapes as given by the two models with different assumptions are similar. The angular distribution of the protons could, however, provide some insight as it differs in the two models.

Global Parameters

In a 4π experiment such as ours, the large number of parameters contain so much information that it is easy to get lost in the details. Global variables can be potentially very interesting in the analysis of such an experiment because they typically use a large fraction of the data of each event to characterize that event. Many global variables have been proposed in the study of multifragmentation. The reduced moment of the Z-distribution discussed in our previous publication⁶ is one example of a

global variable. Another interesting global variable is the eccentricity of the momentum distribution of the event.^{7,8} The eccentricity is obtained by diagonalizing the momentum tensor:

$$Q_{ij} = \sum_{\mu=1}^m p_i^{\mu} p_j^{\mu} \gamma(p^{\mu})$$

and using the major axes, q_1 , q_2 , q_3 as defined such that

$$|q_1 - q_2| \leq |q_2 - q_3| \leq |q_1 - q_3|.$$

q_1 and q_2 are the axes with similar lengths and q_3 is the approximate symmetry axis of the ellipsoid. The eccentricity, ϵ , is then defined as:

$$\epsilon = \left[q_3 - \frac{1}{2}(q_1 + q_2) \right] / (q_1 + q_2 + q_3).$$

This quantity is close to zero for spherical events, is positive for prolate shapes, approaches 1 for the extreme of pencil-like events, and is negative with a value approaching -1/2 for pancake like events. This, together with the angle that q_3 makes with the beam, θ_3 , can be used to gain insight into the decay process as a whole.

Figure 6. The distribution of the eccentricity, ϵ , of the momentum ellipsoid vs. the angle that the major axis makes with the beam, θ_3 .

In Figure 6 we present a contour plot of ϵ vs. θ_3 . We note values of ϵ near 0 which have an almost continuous distribution in θ_3 . There are both positive and negative values of ϵ . This results from

fluctuations due to the finite multiplicities. But the small values of ϵ indicate central collisions and the nearly isotropic distribution in θ_3 also indicates centrality as q_3 can have any orientation.

Figure 7. A comparison of several variables of our data with that of the ALADIN data from GSI. The predictions of the multifragmentation model are also shown for the systems with two Z/A ratios.

Comparison to ALADIN Data

Finally, we compare some observables of these data with observables from the data of the ALADIN group⁹ in which the multifragmentation calculation has been used to explain their observations.¹⁰ In this work, Z_{bound} which is defined as the sum of all detected charge for products having $Z \geq 2$, was used as a global parameter to determine the centrality of the event. In the calculation, the mass of the hot source was estimated using BUU calculations, and the excitation energy of this source was adjusted such that the experimental correlation between the average IMF multiplicity and average Z_{bound} are reproduced. For the central collisions in that work, a mass near 70 having an excitation energy per nucleon of 6 MeV was extracted. This is comparable to the mass and excitation energy that we expect for our system after pre-equilibrium emission.⁶ Figure 7 shows a comparison of Z_{bound} , Z_{max} , M_{mf} , and M_{α} between our $^{40}\text{Ca} + ^{40}\text{Ca}$ data and the central collisions of the ALADIN data. The calculations using the multifragmentation model are also shown for our system as well as an $A=70$ system with the same Z/A ratio as that of the Au nucleus. We note that our data qualitatively follow the same trend. We

attribute the differences to the different Z/A ratios as our system is assumed to have $A = 70$, $Z = 34$ giving $Z/A = .486$ whereas $Z/A = .4$ is the assumed values for the $A = 70$ nucleus decaying in that work. The two calculations with the different Z/A ratios appear to reflect these differences. The exceptions are the Z_{bound} and the M_{α} for our system. The calculation predicts too few alphas which adds to the value of Z_{bound} .

We are continuing our investigation of these comparisons as well as of other data which have a similar mass and excitation energy of the decaying system.

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Mechanisms of Light Charged Particle and Intermediate Mass Fragment Production for the Reaction 220 MeV ^4He + ^{154}Sm

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The use of light ion projectiles, such as ^3He and ^4He , can yield important insights into the production mechanisms for intermediate mass fragments.¹ With light projectiles, one can avoid contributions from various break-up processes and thus have a clearer view of the pre-equilibrium fragment emission seen at forward angles. In addition, because of the relatively low spins involved, one may better understand the role of angular momentum in fragment emission.

In a recent experiment, light charged particles (LCP) and intermediate mass fragments (IMF) ($Z > 3$) have been measured in coincidence with neutrons for the reaction 220 MeV ^4He + ^{154}Sm . The experiment was performed with the neutron ball.² Five, two- to three-element solid state particle detectors were used to detect and identify the charged particles and to measure their kinetic energies and angular distributions. These detectors were placed at angles of -20° , 30° , 50° , 70° , and 90° with respect to the beam. Solid angles ranged from 4.0 msr to 8.6 msr. Typical beam intensities were < 10 pAmps.

From this experiment several things are to be learned. The neutron multiplicity distributions are a measure of the violence of the collision between the target and projectile.³ These multiplicity distributions, measured on an event by event basis in coincidence with charged particles, will therefore allow us to separate LCP's and IMF's produced in peripheral reactions (events with low neutron multiplicities) from those produced in central reactions (events with large neutron multiplicities).

This will provide a measure of the contribution from each reaction process to the total LCP and IMF cross sections. Additionally, the charged particle angular distributions and energy spectra will be examined by gating on various neutron multiplicity folds. These angular distributions and energy spectra could provide new clues as to the spin and energy partitioning between daughter and parent nuclei. Furthermore, it is well known that the anisotropy observed in the angular distribution is in part driven by the shape of the emitting or fissioning nucleus. These shapes derived from the experimentally measured angular distributions can be compared with theoretical calculations of the saddle and scission point nuclear shapes. Such a comparison may provide insight into the dynamical aspects of the decay process.

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NUCLEAR STRUCTURE AND FUNDAMENTAL INTERACTIONS

Nuclear Matter Compressibility from Isoscalar Giant Monopole Resonance

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The nuclear matter ($N=Z$) and no Coulomb interaction) compressibility, K_{nm} , is an important quantity characterizing the nuclear medium since it is directly related to the curvature of the nuclear matter equation of state,¹ $E=E(\rho)$, at the saturation point $(E,\rho) = (-16 \text{ MeV}, 0.17 \text{ fm}^3)$. Accurate determination of K_{nm} is very important for the study of properties of nuclei (radii, masses, giant resonances, etc.), supernova collapses, neutron stars, and heavy ion collisions.²

The study of the isoscalar giant monopole resonances (GMR) in various nuclei provides an important source of information for K_{nm} . The GMR was first discovered in ^{208}Pb at excitation energy³ of 13.7 MeV. Random phase approximation (RPA) calculations using existing or modified effective interactions having $K_{nm} = 210 \pm 30 \text{ MeV}$ were in agreement with experiment.⁴ It is important to note, however, that this commonly accepted value of $K_{nm} = 210 \pm 30 \text{ MeV}$ was deduced using a limited class of effective interactions.

With the increase in GMR data in various nuclei, it became worthwhile to attempt using a semi-empirical approach to deduce K_{nm} . In this approach, which is similar to the semi-empirical mass formula, one writes^{4,5} the compressibility K_A of the nucleus with mass number A , as an expansion in $A^{-1/3}$,

$$K_A = K_{vol} + K_{surf} A^{-1/3} + K_{curv} A^{-2/3} + (K_{sym} + K_{ss} A^{-1/3}) \left(\frac{N-Z}{A} \right)^2 + K_{coul} \frac{Z^2}{A^{4/3}} + \dots, \quad (1)$$

where K_A is defined by

$$K_A = \frac{m}{\hbar^2} E_{GMR}^2 \langle r^2 \rangle. \quad (2)$$

Here $\langle r^2 \rangle$ is the mean square radius of the nucleus and E_{GMR} is taken to be the scaling energy of the GMR defined by

$$E_{GMR} = \sqrt{m_3/m_1} \quad (3)$$

where m_k is the RPA sum rule

$$m_k = \sum_n (E_n - E_0)^k | \langle 0 | r^2 | n \rangle |^2. \quad (4)$$

Note that with the definition (3) for E_{GMR} , K_{vol} in (1) is equal⁵ to K_{nm} .

There have been several attempts in the past⁵⁻¹² to determine K_{nm} using the procedure described by (1) to (4) by a least square (LS) fit to the GMR data of various sets of nuclei. In these attempts, only a very limited number of parameters (1 to 3), mainly K_{vol} , K_{surf} , and K_{sym} , were included in the LS fit using fixed values (deduced from theory) for the other parameters, such as K_{coul} and K_{curv} in eq. (1). Recently, Sharma and collaborators, in a series of papers,¹⁰⁻¹² claimed that a value of $K_{nm} = 300 \pm 20 \text{ MeV}$ is obtained using the recent GMR data of Groningen for the nuclei $^{112,114,116,120,124}\text{Sn}$ and $^{144,148}\text{Sm}$ and including those of ^{208}Pb , ^{90}Zr , and ^{24}Mg . It should be pointed out that this result is quite different from the commonly accepted value of $K_{nm} = 210 \pm 30 \text{ MeV}$. Very recently, Pearson¹³ has pointed out that K_{nm} is strongly dependent on the value assumed for K_{coul} and that the relation between K_{coul} and K_{nm} is model dependent.

In the present study, we take a closer look at the semi-empirical analysis of the GMR data using the procedure (1) to (4) in an attempt to extract a reliable value for K_{nm} . We find that the claim of Sharma *et al.*,¹⁰⁻¹² is not reliable since their analysis is limited in the number of data points and the number of free parameters included in the LS fit. We have attempted to include the entire GMR data set, reconciling differences between different laboratories and taking the parameters in eq. (1) as free parameters. In the following, we first summarize some theoretical and experimental observations

concerning the procedure of eqs. (1) to (4) and then provide some numerical results and conclusions.

We now discuss the following considerations that must be taken into account when using the equations (1) to (4) in a fit to the experimental data for the GMR.

- 1) In using (3) to determine E_{GMR} , the entire GMR energy weighted sum rule (EWSR) must be known experimentally. This appears to be the case for heavy nuclei where the GMR strength is fitted by a Gaussian with centroid E_0 and width Γ . In this case one has

$$E_{\text{GMR}}^2 = E_0^2 + 3(\Gamma/2.35)^2. \quad (5)$$

- 2) In deformed nuclei, a splitting of the GMR strength into clearly identifiable components occurs.¹⁴⁻¹⁷ In this case, eq. (3) cannot be used to obtain E_{GMR} , which corresponds to the spherical configuration. Theoretical considerations indicate¹⁷ that to a good approximation the higher component is shifted upward by an amount proportional to the deformation parameter β . We have therefore included in our analysis the GMR data for deformed nuclei by adopting the centroid E_0 and width Γ of the higher component and adding to eq. (1) the term

$$\beta K_{\text{def}}. \quad (6)$$

- 3) At present, any attempt to include GMR data for light nuclei should be considered with extreme care due to the following reasons:
  - (i) RPA calculations of the GMR predict that the strength is fragmented^{18,19} over quite a large range (over 10 MeV). Therefore, GMR strength must be carefully searched for over a wide range of energy.
  - (ii) The particle decay width^{18,20} of the GMR is quite large (5-10 MeV), particularly for high

energy components. This makes the experimental task of determining the GMR strength distribution rather difficult, and

(iii) For light nuclei, the scaling approximation may not be as good an approximation as in the case of heavy nuclei, introducing¹⁹ errors of about 5% in the determination of E_{GMR} from eq. (3). In this work we also discuss the implication of the present data on GMR in light nuclei.

- 4) In determining K_A from eq. (2), one usually adopts a certain expression for $\langle r^2 \rangle$ with a specific $A^{1/3}$ dependence. The $A^{1/3}$ dependence of $\langle r^2 \rangle$ affects the $A^{1/3}$ expansion of K_A . Since different expressions for $\langle r^2 \rangle$ will lead to different values for the coefficients in the expansion (1) for K_A , adopting theoretical values for some of the coefficients will be inconsistent.
- 5) In previous analyses of the GMR data, such as in refs. 5 and 10-12, the number of free parameters in (1) was reduced by adopting relations between the parameters, such as $K_{\text{surf}} = -K_{\text{vol}}$ and

$$K_{\text{coul}} = \frac{3e^2}{5r_0} \left(\frac{1215}{K_{\text{nm}}} - 12.5 \right) \text{MeV}, \quad (7)$$

obtained from theory.⁵ It should be pointed out that these relations were derived using a limited class of effective interactions and they are not unique.¹³ Therefore, from points 4) and 5) we conclude that all parameters of eq. (1) should be determined by a least square fit to the experimental GMR data.

Extensive investigations of the giant monopole resonance have occurred at three laboratories: Texas A&M, Grenoble, and Groningen. Each has taken spectra into the very small angles necessary to separate monopole from quadrupole strength, a technique pioneered at Texas A&M.³ At Texas A&M, substantial monopole strength was identified in 17 nuclei using inelastic α scattering between 96

and 130 MeV.^{3,8,21-23,31} At Grenoble, monopole strength was observed in 42 nuclei with 100 MeV ^3He scattering,⁷ and in 3 nuclei with α scattering.²⁴ At Groningen, 13 nuclei were investigated with 120 MeV α scattering.^{10,25-28}

The ^3He data yields a much lower monopole strength and somewhat smaller widths than the α data for $A \leq 154$. The Grenoble group later investigated three nuclei with α scattering and obtained results in good agreement with the other α experiments. They conclude²⁴ that the GMR structure "seems to extend further up the high excitation-energy side" in α scattering and provide the possibility that this difference "can be due in part to the choice of subtracted background." In any case, only a portion of the GMR strength is seen in the ^3He scattering.

Of these 75 potential data points, only 27 (9 TAMU, 11 Groningen, 2 Grenoble α , 5 Grenoble ^3He) have EWSR fractions consistent with 100% of the monopole strength. These 27 data points represent 16 different nuclei with $24 \leq A \leq 232$.

At Groningen, a special effort was made to measure GMR parameters in the Sn and Sm isotopes precisely.¹⁰ Spectra were taken over the range 0° to 3° and raytracing used to divide the results into two spectra, one 0° - 1.5° where the monopole is strong, and one 1.5° - 3° where the monopole is weak. The larger angle spectrum was then subtracted from the first to enhance the monopole and the resulting spectrum fit to determine monopole parameters. They reported substantially smaller errors in position of the monopole than other works, though their errors in width are comparable to others.

Errors in GMR parameters from each of these works have three components: 1) Uncertainties in the fitting process due to statistical errors and the appropriateness of the model, usually obtained from the error matrix. 2) Uncertainties in subtraction of the continuum and background, which are subjective and probably arrived at differently by the different groups; and 3) Systematic uncertainties such as energy calibration, absolute yield calibration, etc.

If all of the available data is to be used, it is important to attempt to put the data from different

laboratories on a similar footing. Both the actual value of the energy and width and their uncertainties are important. Systematic differences between different data sets will distort the fits, and data with lower stated uncertainties will dominate the fits. Thus we have explored both the parameters and the uncertainties reported by the different laboratories.

We looked for energy calibration systematic differences by comparing energies obtained for both the GMR and the nearby giant quadrupole resonance (GQR) by the three laboratories. There are 8 nuclei where the GQR and GMR were measured by both TAMU and Groningen. Of the 16 comparisons, in 13 cases Groningen's energies are higher than obtained at TAMU. The 16 point average shows Groningen energies 290 keV higher than the TAMU energies. Two of the three nuclei measured with α scattering at Grenoble were also measured at TAMU. For all four data points, the Grenoble energies were higher, the average being 220 keV. Only the GQR energies were used in the ^3He comparison.

In comparing the uncertainties, we note that the Groningen group reports¹⁰ statistical uncertainties in peak position of typically 70-90 keV. In the TAMU work, these were in the same range, suggesting that the statistical accuracy of the data from the two laboratories is comparable. The statistical contribution to the uncertainties was not reported for the Grenoble work. Systematic differences can be reduced by shifting one of the data sets by the average difference.

This leaves the subjective uncertainties due to subtraction of the continuum and background as the difference between the results from TAMU and Groningen. The primary advantage of the Groningen measurement is that spectra with strong and weak monopole contributions were taken simultaneously, so the experimental conditions do not change between the sets of data. This does lead to excellent subtraction of the quadrupole resonance for which the yield over this angular range is almost constant. For the continuum and background, however, the situation is not as good. The continuum and any background (slit scattering, etc.) are often angle

dependent and, for this, the subtraction technique may not help. As the Groningen data is limited to the excitation range $10 \text{ MeV} \leq E_x \leq 20 \text{ MeV}$, the spectra give few clues as to the shape of the background above or below the giant resonances. In fact, the continuum is not apparent in the spectra shown¹⁰ and there is little basis for determining a continuum shape. Thus, uncertainties due to continuum subtraction could be quite large. The TAMU data extend over a much wider range of energy ($5 \text{ MeV} \leq E_x \leq 80 \text{ MeV}$), allowing a better determination of the continuum shape, and for most nuclei several runs were taken at each angle in differing sequences to reduce errors due to changing experimental conditions. The uncertainties added for continuum subtraction were conservative. Typically, they were chosen as the most a peak energy could be changed by differing continuum assumptions that could not be totally ruled out, ranging from one that changed slowly under the peaks (similar to the background chosen in the Groningen work¹⁰) to one that began near the peaks and increased rapidly, joining to a smooth extrapolation of the continuum above the resonance but excluding ^5He and ^5Li breakup. The Groningen data cannot distinguish these different background possibilities. Thus it is not clear that the overall uncertainties in peak position in the Groningen work are smaller than in the TAMU works.

We have not considered data taken only at larger angles where the GMR cannot be unambiguously identified except in the case of Th and U, where essentially no other data exists. Morsch *et al.*,²⁹ measured ^{208}Pb , ^{232}Th , and ^{238}U using 172 MeV α particles, and we have included this data because these are the heaviest nuclei in which the GMR has been seen. As the ^{208}Pb GMR position agrees with the TAMU value, no correction was made to the Julich work for systematic differences.

The silicon data point requires a special comment. The GMR centroid given⁸ as 17.9 MeV for ^{28}Si is incorrect. The actual centroid and width for the strength reported in the paper are 19.0 MeV and 6.3 MeV.

We chose to accept the TAMU energies and modify the other works by the average difference to correct for systematic errors. At present there is little experimental reason to pick one of the data sets as more accurate on an absolute basis. Where multiple measurements of the same parameter are available, weighted averages (done after correction for systematic errors) were taken.

Using the data of the GMR, we have performed fits for several data sets. Using all the α scattering data for $A \geq 90$ (19 points) we obtained similar results to those obtained with the 7 data points adopted by Sharma *et al.* It should be emphasized that we assumed uncertainties in E_{GMR} about twice those adopted by Sharma *et al.* We then explored including additional data points where the entire sum rule is not seen and cannot be accounted for. First we added all ^3He data points with $A \geq 89$. This reduced the uncertainties slightly. Then we added the lighter nuclei (Zn, Ca, Si) where not all the strength was seen, to ascertain the effects on the fits. For Ca we arbitrarily assumed $E_x \approx 18 \pm 1 \text{ MeV}$ as there is some evidence^{7,8} of monopole strength coincident with the GQR. For ^{28}Si we assumed $E_x \approx 20 \pm 1 \text{ MeV}$ because only 65% of the strength was observed with a centroid of 19 MeV. Probably the rest of the strength lies higher. In this fit we left out the ^{24}Mg point, since it is much lower than ^{28}Si . This resulted in substantially smaller uncertainties for the parameters and illustrates the importance of including lighter nuclei.

Figure 1. Correlation between K_{vol} and K_{coul} . The results shown were obtained using various GMR data sets and parameter sets.

From Figure 1, it is clear that K_{coul} has a large effect on K_{nm} , and including it as a free parameter leads to uncertainties of approximately 50%, except for the 10 point Groningen data set. For this data set, with K_{coul} as a free parameter $K_{\text{nm}} \approx 226$ MeV, rather than the ≈ 300 MeV found by Sharma. Including both K_{coul} and K_{curv} as parameters leads to errors exceeding 100% for all coefficients. On the other hand, K_{def} is well defined at about 35 MeV and fixing it at this value or allowing it to vary has little effect. Adding the ^3He data points with $A \geq 89$ reduces the uncertainties in the parameters slightly. Finally, including the data for elements lighter than Zr helps to further reduce the uncertainties in the parameters. However, it is not possible to pin down the value of K_{nm} with accuracy of better than 50%.

Thus the present complete data set is clearly not adequate to limit the range of K_{nm} to better than about a factor of 1.7 (200 to 350 MeV). Several things need to be done to pin down K_{nm} . We need measurements on considerably more than 16 nuclei and with more variation in mass. To the extent possible, spherical nuclei should be chosen to eliminate effects of deformation. These measurements need to provide the centroid and width of the GMR to better than 150 keV, after taking into account possible uncertainties in the continuum. Significant systematic errors between differing measurements must be removed. The strength distribution in light nuclei must be mapped over a wide energy range. It will be worthwhile to carry out RPA calculations of the GMR with effective interactions that reproduce the ground state properties of nuclei and the strength distribution of the GMR for light as well as heavy nuclei.

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Deuteron Elastic Scattering at 110 and 120 MeV

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We have continued the deuteron elastic scattering cross-section measurements described last year.¹ To the existing data sets on C and ²⁰⁸Pb at 110 MeV, we have added two more on C and ⁵⁸Ni at 120 MeV. The experimental set-up, illustrated in last year's report, differed for the two energies only in that the energy detector was changed. The BaF₂ scintillator was replaced by a NaI scintillator measuring 5.08 cm thick by 1.91 cm diameter that was backed by an EMI 9902KB phototube. This change improved the energy resolution from about 2 MeV full-width at half-maximum for the 110 MeV data to 0.96 MeV for the 120 MeV data. This can be seen in the ⁵⁸Ni spectrum at 10°, shown in Fig. 1, where both the ground state and 1.45 MeV first excited state are clearly resolved. The solid angles for the two data runs at 110 MeV were 0.159 and 0.128 msr, and for the 120 MeV data it was 0.150 msr. The overall systematic normalization uncertainty in our measured cross-sections of 5% arises from target thickness non-uniformity and beam current integration.

Figure 1: The 120 MeV ⁵⁸Ni(d,d)⁵⁸Ni spectrum at 10°. The resolution of the ground state is 0.96 MeV FWHM. Other states are identified at 1.45 MeV and 4.5 MeV.

There are two deuteron global optical model potentials currently available. The first, from Daehnick, *et al.*,² covers the mass range of A=27 to A=238. Some ¹²C and ²⁴Mg data are included at 80 and 90 MeV with reduced weights because not much higher mass data exists at these energies. The full energy range covered is thus 11.8 to 90 MeV. Both relativistic and non-relativistic forms of the potential were extracted, but this made little difference when

the potentials were extrapolated to our data. The relativistic potential, 79DCVF, was used in the analysis below.

The other global potential is from Bojowald, *et al.*³ This potential covers the mass range from A=12 to A=208 and the energy range from 52 to 85 MeV. This group took additional data at 58.7 and 85 MeV on several targets, so their data set includes more higher energy work. Only non-relativistic potentials were extracted.

Both Daehnick and Bojowald optical potentials have the same general form:

$$V(r) = -V_R f(r, r_0, a_0) - iW_S f(r, r_I, a_I) \\ + i4a_I W_D \frac{d}{dr} [f(r, r_I, a_I)] \\ + V_{LS} \left(\frac{\hbar}{m_\pi c} \right)^2 (L \cdot S) \frac{1}{r} \frac{d}{dr} [f(r, r_{LS}, a_{LS})] \\ + V_{Coulomb}$$

where

$$f(r, r_i, a_i) = \left[1 + \exp \left(\frac{r - r_i A^{1/3}}{a_i} \right) \right]^{-1}$$

is the standard Woods-Saxon form.

Some higher energy data is also available from Nguyen Van Sen *et al.*⁴ Cross-sections along with vector and tensor analyzing powers were measured on ⁵⁸Ni from 200 to 700 MeV, and ⁴⁰Ca at 200 MeV. This group found that the Daehnick potential described the shape of their data well, and provided a good starting point for a fit.

Our carbon data, along with the predictions of the global optical potentials and our best fits, are shown in Figs. 2-3. The data vary smoothly from the lower energy data and, as expected, are slightly smaller in cross section and slightly more forward peaked. Note that the Daehnick potential is even more forward peaked than the data at 110 MeV, and the predicted cross section is also larger than the data at scattering angles beyond the first diffraction maximum. At 120 MeV the magnitude of the cross section is about right, suggesting that the calculated cross section of this global model falls faster with energy than the

data in this energy range and at this mass. The Bojowald potential has the correct phase, but is too large outside the second diffraction maximum at both energies. Neither of the global models has sufficient diffraction to agree with the data. The fits, carried out with the optical model search code CUPID⁵, using the two global potentials as starting points, describe the 110 MeV data well. The fitting was done by chi-square minimization. The 120 MeV data was fit both with the extrapolated potentials and with the potentials that resulted from the fits to the 110 MeV data. Both fits that we obtained starting from the extrapolated global potentials were qualitatively poor. The best fit shown in Fig. 3 is the result of using the fit to our 110 MeV data as the starting point. In all cases the diffraction peaks are sensitive to whether or not the spin-orbit term is allowed to vary for mass 12, suggesting that the additional information that could be gained from polarized ($\bar{d},d$) scattering would be useful.

Figure 2: The 110 MeV carbon data, along with the predictions of two global optical model potentials, and the best fit to the data from these potentials. The solid line is the extrapolation of the Daehnick potential, the dashed line is the extrapolation of the Bojowald potential, and the dotted line is the best fit curve, which in this case used the Bojowald potential as a starting point. In this and the succeeding figures, the statistical errors are much smaller than the data points at the small angles and are comparable to the size of the data points at the largest angles measured.

The 120 MeV ^{58}Ni data is shown in Fig. 4, along with the associated potentials and fits. The extrapolation of the Daehnick potential works quite well in this case. The fit starting from the Daehnick parameters only improves the agreement a small amount at the diffraction minima. The Bojowald potential, on the other hand, again does not have enough large angle absorption to fit the data, although this discrepancy is smaller than it is for the carbon target.

Figure 3: The 120 MeV carbon data, potentials, and fits, as in Fig. 2. The best fit curve here used the Daehnick 110 MeV best fit curve as a starting point.

Figure 4: The 120 MeV ^{58}Ni data, potentials, and fits, as in Fig. 2. The best fit curve used the Daehnick potential as a starting point.

Figure 5 shows our 110 MeV ^{208}Pb data. The cross section predicted by the Daehnick potential is again slightly out of phase with the data, this time with the potential less forward peaked, while the predicted magnitude agrees quite well. The Bojowald potential is too low in magnitude at large angles, but has the correct phase. Again, both starting points provide fits that agree with the data quite well.

Table 1 shows the optical model parameters from the extrapolated global potentials and the fits on all targets and energies. In general, the results of the fits were stable against modest changes in the starting parameters. Both global potentials were qualitatively close. From this limited data set, only a few significant mass and energy dependent patterns can be seen. The Daehnick potential has too large an a_0 across the mass range at this energy. It also seems to have an energy dependent absorption that does not agree with the $A=12$ data. Since the potential was

Figure 5: The 110 MeV ^{208}Pb data, potentials, and fits, as in Fig. 2. The best fit curve used the Daehnick potential as a starting point.

derived for $A=27$ to $A=238$, this is an extrapolation that cannot be expected to work well in any case. The absorption on $A=58$ and $A=208$ agrees very well with the data. The Bojowald potential, on the other hand,

has a systematic variation of the absorption as a function of mass at these energies. It is much too small at $A=12$, too small at $A=58$, and too large at $A=208$. With the data available, both potentials provide comparable starting points for optical model fits.

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TABLE I. Optical Model Parameters. The asterisks indicate the best fit parameters for each target and energy.

	V_R	r_0	a_0	W_s	W_D	r_i	a_i	V_{LS}	r_{LS}	a_{LS}	Volume Real	Integrals Imag.	(J/A) L-S
110 MeV C													
Daehnick	59.18	1.17	0.85	10.82	4.60	1.27	0.67	3.68	1.07	0.66	794.	268.	19.0
D-fit	60.00	1.16	0.77	11.34	4.75	1.32	0.70	3.70	1.12	0.74	721.	315.	20.0
Bojowald	58.67	1.18	0.72	8.58	4.07	1.27	0.82	6.00	0.87	0.87	685.	279.	26.0
B-fit*	60.17	1.14	0.75	9.12	8.68	1.36	0.74	5.44	0.92	0.90	682.	303.	25.0
120 MeV C													
Daehnick	56.35	1.17	0.86	12.00	3.72	1.27	0.67	3.36	1.07	0.66	767.	256.	17.4
D-fit	58.30	1.19	0.79	10.72	3.81	1.35	0.71	3.08	1.02	0.75	762.	293.	15.3
D110-fit*	55.48	1.16	0.78	6.99	3.85	1.33	0.79	4.14	1.42	0.83	672.	260.	28.4
Bojowald	56.27	1.18	0.72	9.90	3.13	1.27	0.82	6.00	0.87	0.87	657.	265.	26.0
B-fit	54.24	1.15	0.75	10.60	3.15	1.26	0.84	5.99	0.86	0.81	622.	281.	25.6
B110-fit	60.20	1.15	0.80	8.14	4.18	1.37	0.76	5.61	0.87	0.84	740.	296.	24.1
120 MeV ^{58}Ni													
Daehnick	60.41	1.17	0.86	12.00	3.72	1.27	0.78	3.36	1.07	0.66	550.	192.	6.0
D-fit*	59.11	1.14	0.84	12.24	3.42	1.28	0.82	6.36	1.18	0.89	501.	203.	12.6
Bojowald	62.66	1.18	0.77	9.90	4.78	1.27	0.85	6.00	0.93	0.93	553.	203.	9.4
B-fit	59.99	1.15	0.75	9.87	4.60	1.24	0.89	6.16	1.04	1.22	494.	197.	10.9
110 MeV ^{208}Pb													
Daehnick	69.05	1.17	0.85	10.82	4.60	1.27	0.90	3.68	1.07	0.66	532.	165.	2.8
D-fit*	68.37	1.18	0.81	10.94	4.65	1.29	0.87	5.24	1.11	1.30	538.	172.	4.2
Bojowald	74.71	1.18	0.84	8.58	7.85	1.27	0.89	6.00	1.01	1.01	588.	184.	4.3
B-fit	68.17	1.19	0.81	8.14	7.33	1.27	0.85	6.54	1.06	1.14	545.	168.	5.0

Projectile Breakup Reactions Induced with 30 MeV/u ^{16}O and ^{20}Ne

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Breakup reactions are commonly divided into two categories: relatively slow, sequential breakup processes and faster, direct breakup reactions. While sequential breakup is certainly a well documented process, direct breakup remains a somewhat controversial issue for a number of projectiles. Probably, the most compelling evidence for this mechanism comes from studies of reactions such as the breakup of ^7Li into $\alpha + t$, which show broad structures in the relative kinetic energy distributions of the fragments just above the dissociation threshold.¹⁻³ Additional studies of breakup reactions are needed to clarify the underlying reaction mechanisms. At the same time, these investigations could provide important astrophysical information. As pointed out in Ref. 4, the Coulomb contributions to both resonant and non-resonant breakup may yield cross sections for their inverse counterparts, namely, resonant and non-resonant radiative capture reactions.

As discussed previously, we have investigated the breakup of 30 MeV/u ^{16}O and ^{20}Ne projectiles on a number of targets using high resolution techniques.⁵ These studies have provided a wealth of information not only on projectile breakup reactions, but also on a wide range of other breakup processes. These could be categorized as reactions that involve charge exchange, pickup and stripping of single nucleons, and various types of multi-nucleon transfer. Although from a technical point of view these measurements are relatively simple, they are yielding new results relevant to nuclear structure and nuclear dynamics. To give one a flavor for the data, we will concentrate on just one aspect, namely, excited state populations.

One of the major goals in medium energy, heavy ion physics involves elucidating the thermodynamic properties of highly excited nuclei. Determination of the nuclear temperature plays a key role in this area. During the last few years, a number of experiments

have been performed to obtain the nuclear temperature from excited state populations.⁶ This method assumes the populations of the excited states follows a simple Boltzmann distribution.⁷ In many instances, such an analysis has yielded somewhat puzzling results.

Figure 1. Sum energy spectrum for the breakup of ^{16}O into $^{12}\text{C} + \alpha$ observed with a ^{58}Ni target.

Because a wide variety of discrete states have been observed in the current studies,⁵ it is instructive to see what is revealed from an analysis of the yield of excited states. Figure 1 shows the laboratory sum energy spectrum for α particles and ^{12}C nuclei for the $^{16}\text{O} + ^{58}\text{Ni}$ system. One sees the three structures previously observed for similar reactions⁵: namely, a high energy, elastic breakup peak, a somewhat lower energy peak that corresponds to reactions that leave the ^{12}C in its first excited state, and, finally a continuum associated with the myriad of target/ projectile excitations. Figure 2 shows relative energy spectra for the same system for the sum energy gates indicated in Fig. 1. All of the

well-defined peaks in Fig. 2 can be assigned to known states in ^{16}O .

Figure 2. Relative energy spectra for $^{12}\text{C} + \alpha$ for the $^{16}\text{O} + ^{58}\text{Ni}$.

One sees a fairly dramatic change in the intensity pattern of the peaks as the apparent energy loss increases. Figure 3 shows the cross sections of peaks A-F divided by the degeneracies as a function of excitation energy in ^{16}O for the $^{16}\text{O} + ^{58}\text{Ni}$ system. Starting at the top of the figure, the results are shown for the sum energy gates 4-9. The results generally follow a linear dependence which is expected for statistical equilibrium. Least square fits to the data in Fig. 3 all yield nearly the same temperature, 2.1-2.5

MeV. There is essentially no systematic dependence of T on the apparent energy loss, which ranges from about 30 to 90 MeV. Similar analyses performed on the data for $^{16}\text{O} + ^{120}\text{Sn}$ and $^{16}\text{O} + ^{208}\text{Pb}$ yield essentially the same temperatures.

Figure 3. Normalized yields of various excited states in ^{16}O as a function of excitation energy for the $^{16}\text{O} + ^{58}\text{Ni}$ system. From top to bottom, the data sets refer to gates 4-9 (see Fig. 1).

The above is a curious result. Based on previous measurements with low energy, heavy ion reactions, one expects the excitation energy to divide about equally between the fragments for small energy losses. For larger energy losses, the excitation energy should divide according to the masses of the fragments. In contrast, if one assumes that the primary excitation mechanism is a binary process, the current results imply that the excitation energy of the projectile stays nearly constant while more excitation energy is deposited into the target nucleus. Clearly, our understanding of how the excitation energy is partitioned between the fragments produced in heavy ion reactions is incomplete.

We are currently investigating the excited state populations associated with other coincidences between α particles and heavy ions to see if they follow a similar pattern.

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Feasibility Study of the Knockout Reaction ${}^7\text{Li}(\alpha, 2\alpha){}^3\text{H}$

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The radiative capture of ${}^3\text{H}$ by ${}^4\text{He}$ to produce ${}^7\text{Li}$ is a process of considerable astrophysical interest¹ as it may provide insight into the relatively low abundance of this element in the universe. This abundance is thought to reflect both its primordial nucleosynthesis in the Big Bang expansion and to some extent its subsequent production in massive stars.

For astrophysical applications, measurement of this cross section are needed at very low (≈ 10 keV) relative energies (ϵ) between the ${}^3\text{H}$ and ${}^4\text{He}$ particles. The cross section for this reaction can not be directly measured with accelerated particle beams because of the very low energies. Following suggestions made by Mukhamedzhanov,¹ it may be possible to extract the astrophysical S-factor for $\epsilon \approx 0$ from the knockout reaction ${}^7\text{Li}(\alpha, 2\alpha){}^3\text{H}$. A knockout reaction is a fast process in which the projectile (in this case an α particle) removes a single nucleon or a cluster of nucleons acting as a single particle (again, an α) from the target nucleus without itself being captured. The S-factor derived from this cross section provides the data in the astrophysical region, assuming the S-factor displays a weak dependence on energy.

In brief, Mukhamedzhanov's idea goes like this: At very low relative energies, the radiative capture process occurs at a large separation distance because of the long range Coulomb repulsion between the particles. Theoretically, therefore, the cross section should be determined by the relative wave function, which at large distances, should essentially be a Coulomb wave function. While the form of this wave function is known, its absolute magnitude is not. By measuring the cross section for ${}^7\text{Li}(\alpha, 2\alpha){}^3\text{H}$ at one energy, under specific kinematical conditions, the Mukhamedzhanov formalism yields the required normalization factor from which one can derive the S-factor, and ultimately estimate the capture cross section in the energy regime of astrophysical interest (< 10 keV).

We have recently performed a couple of feasibility studies to test the above method. Accordingly, we have measured α - α coincidences in two solid state charged particle detectors placed at $+45^\circ$ and -45° with respect to the beam in a coplanar geometry. For these angles, the triton is expected to behave as a spectator at high incident energies. In the limit that the triton has zero kinetic energy the summed energies of the two α 's is $E_{\alpha\alpha} =$

$E_{\text{beam}} + Q$ which yields 97.5 MeV for a 100 MeV beam.

A self-supporting 2.71 mg/cm^2 ${}^7\text{Li}$ target was used in the measurements. Because of the high chemical reactivity of Li, several precautions were made to insure as little contamination of the target as possible. The first precaution was to store the target in mineral oil. The second was to have a continuous flow of Ar through the scattering chamber. The mineral oil was rinsed off with hexane, and the target was quickly transferred to the scattering chamber. The chamber was sealed and immediately evacuated. Following this procedure, the Li foils proved to be stable.

During the measurements, the target was inundated with $\approx 5 \text{ enA}$ of 100 MeV α particles. The beam was kept low because the tests were performed in the scattering chamber of the neutron ball. Even at these low intensities, a considerable number of α - α coincidences were recorded in a few hours.

Figure 1. Summed energy spectrum for two α particles measured in coincidence. The quasi-elastic knockout peak is indicated in the figure.

In the offline analysis, gates were set on the α - α coincidences. Figure 1 is a plot of number of events versus the summed energy $E_{\alpha\alpha}$. This spectrum has been corrected for the energy loss in the target and for random coincidences. The quasi-elastic knockout process is associated with the peak centered at 94.5 MeV. Although this is a value 3% lower than the expected value, this is nonetheless the knockout process as evidenced by the narrow width of the peak (FWHM $\approx 4 \text{ MeV}$). This discrepancy is not thought significant. The telescope consisted of two elements, a $300 \mu\text{m}$ detector for the Δ -E, and a $1000 \mu\text{m}$ detector for the E. This was not adequate to stop the elastics. The energy calibrations were therefore obtained by extrapolation from a ${}^{241}\text{Am}$ point.

Our feasibility study indicates that the cross section for the reaction ${}^7\text{Li}(\alpha, 2\alpha){}^3\text{H}$ is easily measurable to a statistical accuracy of a few percent without significant interference from light contaminants. In the very near future, we intend to carry out measurements of the ${}^7\text{Li}(\alpha, 2\alpha){}^3\text{H}$ reactions at both 100 and 220 MeV incident energies. The equality of the extracted S-factors will provide a critical test of the theory as well as the applicability of the experimental technique to similar reactions of astrophysical importance.

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GDR γ Decay of ^{142}Nd Nucleus Produced by $^{16}\text{O} + ^{126}\text{Te}$ and $^{22}\text{Ne} + ^{120}\text{Sn}$ Reactions at $E^* = 150$ MeV

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There have been a number of investigations¹⁻⁴ to investigate the entrance channel effects in the formation and decay of compound nuclei produced in heavy ion collision processes. Recently Thoennessen *et al.*⁵ reported that for compound systems in $A=160$ region, the GDR γ rays exhibit significant differences in the spectral shapes depending on the entrance channel mass asymmetry of the reaction. For compound systems in the $A=110$ region, no such effects were observed. We have studied the GDR decay of ^{142}Nd nucleus populated at $E^* = 150$ MeV by different target-projectile combinations ($^{16}\text{O} + ^{126}\text{Te}$ and $^{22}\text{Ne} + ^{120}\text{Sn}$), having mass asymmetries around the liquid drop Businaro-Gallone critical mass asymmetry α_{BG} . The experiment was carried out at the $k=500$ superconducting cyclotron at Texas A&M University, USA. The γ rays were measured in coincidence with the evaporation residues using two 19-element BaF_2 arrays. The evaporation residues were measured by the TOF technique using two large area MWPCs at forward angles. Fig. 1 shows the γ ray spectra measured in the two reactions. The GDR parameters (E , Γ) were determined after subtracting the continuum as shown in the figure. The values of E and Γ were found to be the same for both the reactions within the errors. These values are shown in Fig. 2. The GDR width at $E^* = 150$ MeV is quite large compared to that expected for the ground state, and follows the systematics⁶ seen for the $A=100$ region. There is no noticeable entrance channel effect in the GDR spectra due to mass asymmetry change in a limited region around α_{BG} . Calculations were carried out using the dynamical model of Feldmeier,⁷ which also do not show much difference in the fusion dynamics except at large initial angular momenta for the two systems. Further measurements for more symmetric target-projectile combinations and as function of angular momentum would be needed to establish the role of α_{BG} in the dynamics of the fusion reactions in this mass region.

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Fig. 1

Fig. 2

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Z_u Dependence of Correlated Positron-Electron Peak Cross-Sections

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The origin of the narrow correlated e^+e^- peaks discovered in superheavy nuclear collision experiments at GSI Darmstadt,¹ remains an unsolved mystery in nuclear physics. In last year's report, we presented the results of a first experiment at the K500 using the High Efficiency Coincident Lepton Spectrometer, in which preliminary evidence for e^+e^- peaks in Xe + Au collisions was found.² Two candidate lines were observed at sum-energies (i.e., the sum of the measured kinetic energy of the coincident positron and electron) of 965 and 652 keV. The existence of correlated peaks in such a light collision system as Xe+Au (with combined nuclear charge $Z_u = 133$) would have important implications for several theoretical speculations on the origin of these lines.

This year, we have continued our investigation of Xe+Au collisions, in an attempt to confirm the existence of these candidate lines. We ran for two weeks with a ~ 0.5 particle nA $^{129}\text{Xe}^{17+}$ beam incident on 0.8 mg/cm^2 ^{197}Au foils. A problem with one of our four PPAC heavy-ion detectors somewhat limited the data accumulation rate, but we nonetheless collected 100,000 e^+e^- events, bringing our total data sample for Xe+Au collisions to over 150,000 events, almost twice the total number of e^+e^- pairs detected throughout the lifetime of the original EPOS spectrometer at GSI.

Results

We have so far analyzed this second data sample completely independently of the first, in order to test the reproducibility of the previously observed candidate lines. The analysis procedures have been improved to substantially reduce backgrounds, by

first excluding events with multiple hits in either the upstream or downstream segmented electron detector, by narrowing the positron time-coincidence conditions, and by averaging over many more beam micropulses for chance-coincidence background subtraction.

Figure 1. Sum-energy spectrum of coincident e^+e^- pairs, emitted from 5.9-6.1 MeV/u Xe+Au collisions, gated on heavy-ion scattering angle range $49.9^\circ < \theta_{\text{Xe}} < 67.7^\circ$.

Comparing the two datasets, we find that the general shape and magnitude of the positron, coincident electron, and e^+e^- sum and difference-energy distributions are consistent. Of the two candidate lines, we again find evidence in the present data for a high energy line, observed here at ~ 980 keV, slightly shifted from the previous position of 965 keV. Energy shifts of this magnitude have been apparent previously when comparing different GSI experiments. This feature, shown in Fig. 1, appears in both the opposite and same hemisphere lepton

detector combinations, compared with primarily opposite hemisphere combinations in the first run. The observed intensity is 45 ± 18 events.

The 650 keV candidate line was observed previously in close nuclear collisions. This cut applied to the present data (Fig. 2) shows no evidence for a line at 650 keV. However, there appears to be a slight excess of events at the energies of the two most prominent GSI lines. We observe 60 ± 30 events at 620 keV, and 40 ± 26 events at 830 keV. We noted a similar excess near 800 keV in the first run (see Fig. 6 in Ref. 2). We conclude that although the 650 keV candidate line is not reproduced, one or both of the GSI 810 and 620 keV lines appear to be produced in Xe + Au collisions with much reduced cross-sections.

Figure 2. Sum-energy spectrum of coincident e^+e^- pairs, emitted from 5.9-6.1 MeV/u Xe+Au collisions, gated on heavy-ion scattering angle range $58.7^\circ < \theta_{Xe} < 67.7^\circ$.

In the present experiment, we corrected a problem in the first run with the absolute event normalization and can now report preliminary production cross-sections for the observed structures. These are summarized in Table I. Expressing the peak intensities as a production probability per scattered heavy-ion in a given angular region yields values which are very sensitive to the exact cut because of the rapidly varying Rutherford cross-section. We therefore express the peak

intensity as a cross-section normalized to the heavy-ion solid angle (CMS), for a more direct comparison with the GSI data.

Table I. Peak energies and cross-sections, normalized to heavy-ion solid angle, for prominent features observed in each of our two Xe+Au runs.

Run I		Run II	
965keV	0.11(3) $\mu\text{b}/\text{sr}$	980keV	0.08(3) $\mu\text{b}/\text{sr}$
652keV	0.28(9) $\mu\text{b}/\text{sr}$	-	-
-	-	620keV	0.23(12) $\mu\text{b}/\text{sr}$
810keV	0.07(4) $\mu\text{b}/\text{sr}$	830keV	0.15(10) $\mu\text{b}/\text{sr}$

Figure 3. Production cross-sections e^+e^- peaks measured in Xe+Au (HECLS), U+Ta (EPOS), and U+Th (EPOS) collisions, plotted v. combined nuclear charge, Z_u . Power-law fit yields $d\sigma_{pk}/d\Omega_{HI} = Z_u^{11.6 \pm 0.6}$, shown by the solid curve with 1 σ confidence bands given by the dashed curves.

Figure 3 compares the HECLS and EPOS peak cross-sections, plotted as a function of the combined nuclear charge. The much smaller cross-sections in Xe+Au imply a moderately steep dependence on Z_u . A best fit of the data to a power-law yields an exponent of 11.6 ± 0.6 . Based on the tabulated cross-sections for isolated structures, we estimate a very conservative upper limit on the existence of

unresolved features of $< 0.5 \mu\text{b/sr}$. This yields a lower limit on the exponent for a power-law fit, suggesting that the peak cross-section scales more steeply than at least Z_u^6 .

Summary

In summary, our preliminary observation of correlated e^+e^- peaks in Xe+Au collisions has been confirmed in a second run with more data. A ≈ 970 keV sum-energy line is observed in the two independent runs at a 2.5σ to 3σ confidence level. Weak indication of previously observed GSI lines, most prominently at 810 keV, is also observed at a 1.5σ level in both runs. We estimate that the production cross-sections of the peaks scale with the combined nuclear charge more steeply than Z_u^6 . In future runs, we will further explore the Z_u dependence of the peaks with other combinations of projectile and target nuclei.

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Progress on the MEGA Experiment

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During the past year, we have continued our work on the photon detector for the MEGA experiment at Los Alamos. A detailed description of the detector was given in last year's report.¹

The MEGA collaboration achieved several major milestones during the past year. The inner two photon pair spectrometers were installed in essentially their final form for the summer, 1992, run cycle. These were the first pair spectrometers which have been constructed with delay line cathodes and reliable MWPC's, thus allowing us to obtain accurate z information regarding shower locations and evolution from the wire chambers and to utilize our scintillator-MWPC first-stage trigger, both for the first time. Since the summer run ended, construction of the final pair spectrometer has been completed, and its installation is well underway as this is being written.

The summer, 1992, run cycle also represents the first time that the entire positron spectrometer system, consisting of eight cylindrical MWPC's to track the positrons and two scintillator barrels to measure their times, was assembled. Although the delay line z resolution was not as good as we had hoped, and there were significant noise and oscillation problems with the electron chamber electronics, the system worked sufficiently well that we also obtained our first physics data during the summer of 1992. At present, data taken during the run on both the $\mu \rightarrow e\gamma$ decay rate and the Michel parameter ρ in normal muon decay are being analyzed. We expect to reach a sensitivity for the $\mu \rightarrow e\gamma$ branching ratio close to that of the current world limit, based on approximately 6 days of data at low beam intensities. Meanwhile, we expect to achieve overall uncertainties

in the Michel parameter ρ of approximately ± 0.001 statistical and ± 0.0015 systematic, compared to the current best value 0.7518 ± 0.0026 .²

In addition to our work on the MEGA photon detector system, our group has played an active role in the measurement of the Michel parameter ρ in normal muon decay with the MEGA positron spectrometer. We made significant contributions to the original design and proposal for the measurement, and have continued to be one of the lead groups in this effort. At present, one of our students, F. Liu, is analyzing the ρ parameter data that was taken during the summer 1992 run cycle for her Ph.D. thesis. We also now have the primary responsibility for maintaining and upgrading SED, the graphical single-event display software for the experiment.

During the past year, our efforts have focused primarily on the 1992 run, analysis of its results, and preparation for data taking with the full three-layer detector beginning in July, 1993. We also completed the analysis of the inner Bremsstrahlung data that was taken during the summer of 1990. The rest of this report describes our recent work on the tasks outlined above.

Software Development

In addition to the photon arm pattern recognition and event reconstruction routines, our group has the responsibility for maintaining and upgrading the experiment-wide event display package SED and the photon arm Monte Carlo program PARMMC. Several features have been added to SED over the past year, some dictated by the evolution of our hardware, but many to integrate SED more closely with our analysis codes.

The primary modification to PARMMC that we made this past year was to configure it to handle the new geometry of the outermost pair spectrometer that was adopted at a collaboration meeting in January, 1992. Each of the two inner pair spectrometers have three contiguous, 0.8 cm thick, wire mesh drift chamber layers, located just outside the cylinder which supports the delay lines and the outer Pb converter foil of that spectrometer. The outer pair

spectrometer includes three drift chamber layers in the same geometry as the inner two pair spectrometers. But it also contains a fourth wire mesh drift chamber layer located 2 cm outside the third layer, as well as "charge-sweeping" wires between layers 3 and 4 and outside of layer 4. The extra drift chamber layer helps to reconstruct high energy photon showers such as we obtain during our $\pi^0 \rightarrow 2\gamma$ calibration runs, while the charge-sweeping wires reduce cross talk due to ionization outside of the drift chamber cells themselves. PARMMC now includes these additional elements in its simulations.

Electronics

In last year's report, we discussed the changes that were made in the electronics following the '90 test run. The scintillator electronics that we used in the '92 run performed well and no subsequent modifications have been made to them. All of the electronics for the full detector system were completed during this past year and are now being installed at Los Alamos for a data run with the full three layers of photon detector this summer.

Major modifications to the delay line preamplifier design were made after the '92 run. We experienced two electronic problems with the preamps that forced us to make revisions. One problem was that about 20% of the preamps oscillated when they were plugged into the motherboard. In some cases, the problem was traced to a slight misalignment of the components while in other cases we could not locate the problem. A slightly larger feed-back capacitor on the first stage eliminated the oscillation on some boards. The other problem was that the gain of the preamp was dependent on the dc voltage supplied to the board. This is a feature of the MAR-1 amplifier which was used for the second stage of the preamp. An additional concern was the large power dissipation in the preamp. Finally, as noted below, the z resolution that we obtained with the delay lines was approximately 1 cm FWHM, compared to the 5-6 mm FWHM that we were anticipating. This was due in part to the low CFD threshold settings that we

were forced to use because the delay line pulse heights were less than we observed in the test chamber in 1990.

Since the run, we have redesigned the delay line preamplifier in conjunction with the U of H electronics group. The basic two-stage amplifier design has been preserved. The new design replaces the OPA-621 with an Analog Devices AD829, while modifying the feedback components to increase the gain and decrease the bandwidth. The second stage of the original preamp design (a Mini-Circuits MAR-1 monolithic amplifier) has been replaced by an Analog Devices AD811 current-mode op-amp, again configured for increased gain and decreased bandwidth. The net result of these changes is to increase the overall gain from 120 to ~ 300 , slow the rise time from 5 ns to 12 ns, and leave the peak-to-peak noise unchanged (~ 6 mV). The power supply requirement has been reduced to < 20 mA/channel, while the power supply voltage may vary from ± 5 V to ± 12 V with minimal gain shifts. The reduced bandwidth should improve the system stability without degrading the time resolution significantly, since the intrinsic rise time of the delay lines is 15-25 ns depending on the propagation distance. Clearly the improved signal-to-noise should improve the time resolution, and thus the z resolution, of the delay line CFD's. As this is being written, the U of H group is beginning to test the first batch of preamplifiers which were mass produced using the new design.

The CFD's for the delay lines were described in last year's report. Generally they worked well during the 1992 run after a minor modification was made to the gate circuitry to eliminate cross talk problems on the backplanes to which they mounted. U of H has now fabricated the remaining CFD's required for the third pair spectrometer using the same design.

Final Analysis of the 1990 Data

1992 saw the conclusion of the ongoing analysis of MEGA photon arm data obtained in late 1990. The algorithms developed during the analysis of a substantial subset of the available Inner Bremsstrahlung data set were applied to the entire

data set. The original data set contained 1.87×10^6 first-stage high energy gamma triggers. The final data set, after application of the second stage trigger and fitting algorithms, and the filtering out of background including Compton scattered electrons and hard Bremsstrahlung events, contained $\sim 67,500$ good shower events. The resultant perpendicular momentum spectrum is shown in Fig. 1.

Figure 1. Final comparison between the measured photon transverse momentum spectrum from the 1990 run and our Monte Carlo simulation. The solid curve includes the combined contributions of photons from inner Bremsstrahlung muon decay and positron annihilation in flight in the muon stopping target. The latter contribution, which is small but critical to obtain good agreement, is also shown separately as the dotted curve.

A statistically equivalent Monte Carlo data set is shown for comparison. In general the agreement is very good. The only notable discrepancies are that Monte Carlo slightly overestimates the yield at the peak and underestimates it near 46 MeV/c. Figure 2 shows the agreement in the endpoint region. This is the most important area for understanding the background that inner Bremsstrahlung will present in the $\mu \rightarrow e\gamma$ search. It is worth noting that the good agreement between the Monte Carlo and the real data demonstrated by Figs. 1 and 2 were only obtained after a previously underestimated source of background photons was investigated. The Monte

Carlo simulation was modified to include the effect of photons produced in the planar 0.5 mm Mylar target through the annihilation in flight of energetic Michel positrons traversing the target. Meanwhile, there is a 10% uncertainty in the muon stopping rate, which provides a relative normalization uncertainty between the data and the Monte Carlo.

Figure 2. Final comparison between the observed photon spectrum from the 1990 run and Monte Carlo simulations, as in Fig. 1. This view focuses on the endpoint region which is important to estimate the random background contribution that these photons make to the $\mu \rightarrow e\gamma$ search.

Analysis of the 1992 $\mu \rightarrow e + \gamma$ Data

M. Dzemidzic of U of H is the primary individual working on the analysis of the summer 1992 photon arm data. He will use this data for his Ph.D. thesis. We are working closely with him on developing new algorithms for unraveling photon arm events using the z information that is available from the delay lines. Much of the work to date has focused on determining drift chamber efficiencies and the z resolution of the delay lines. The z resolution is determined by using the electron arm chambers to track cosmic rays and then project these events out to the photon arm. Comparing the measured and predicted z position of the events provides a determination of the z resolution. This technique

depends on a thorough understanding of the alignment of the electron arm relative to the photon arm and on the pointing accuracy of the electron arm. From early comparisons between the measured and predicted z values, we found that it is necessary to account for the break that occurs in the center of the chamber where two short delay lines are joined to produce a "single" delay line that runs the full length of the photon chamber. Figure 3 shows a composite of ten delay lines where the residuals from predicted z and measured z have been plotted. The results from this set of delay lines indicates that the z resolution is on the order of 1 cm (FWHM), after removing the pointing uncertainty. This result is preliminary since electron arm analysis is still continuing and changes in the electron arm geometry will affect the z resolution that we observe in the photon arm.

Figure 3. The difference between the measured z coordinate from our delay lines and a fit to the remaining hits in the event, based on cosmic ray triggers. The solid curve is a smoothed version of the residual spectrum.

The z information in the photon arm determines the longitudinal momentum of the pairs and the z location of the vertex. It also provides additional constraints for the pattern recognition algorithms. Recently, we have been working with Mr. Dzemidzic to include this information in the pattern recognition algorithms that we have built up over the past few years. In the past, one of the problems that we have encountered in using "end views" for pattern recognition is that the vertex for some events gets obscured when one member of the pair spirals back through the cells that are adjacent to the vertex

region. Using the z information as we indicated above allows us, in many cases, to distinguish between the two different tracks and thus we can eliminate the ambiguity in these cases.

Measurement of the Michel Parameter ρ

In the fall of last year, we collected the data for a measurement of the Michel parameter ρ as planned. We will refer to this experiment as RHO in the following. The objective of RHO was to measure ρ to an accuracy of $\delta\rho/\rho = 0.001$, which is about three times better than the current best value: $\rho = 0.7518 \pm 0.0026$.¹ This result will further test the Standard Model and allow us to search for evidence suggesting physics beyond it.

Figure 4. An end view of the positron spectrometer which is used for both the $\mu \rightarrow e\gamma$ search and for the ρ measurement.

The experiment was carried out using the existing MEGA detector system. ρ can be determined by measuring the positron energy spectrum in normal muon decay. An end view of the positron spectrometer part of the MEGA detector is shown in Fig. 4. It consists of 180 strips of plastic scintillators and 8 multi-wire proportional chambers (MWPC's). The scintillators form two hollow barrels coaxial with the beam, located upstream and downstream from the target, which is installed at the center of the detector system. The chambers are arranged such that seven smaller chambers (12 cm in

diameter) surround a larger central chamber (22 cm in diameter), often referred to as the seven dwarfs and Snow White respectively. The electron spectrometer is contained within the innermost region of the bore of a superconducting solenoid that generates (parallel to its own axis) a 15 kG magnetic field. The muon beam enters along the axis of the solenoid, stops in a thin vertical target and decays at rest. Under the influence of the magnetic field, the positron from a muon decay is confined to the central region. The trigger for a normal muon decay event is given by the OR of the finely segmented plastic scintillators. The track of the positron, which is a helix, can be reconstructed from the coordinates of chamber hits. The locations of the MWPC hit wires provide the (x,y) pairs, while the z -positions are calculated from the intersection of spiral cathode strips and the wires. The momentum of the positron is then derived from the parameters of the helix.

A surface μ^+ beam was tuned to have a momentum of 28 MeV/c with a relative momentum spread $\Delta P/P$ of 6% FWHM. The polarization of the muon beam was greater than 99%, with the muon spin opposite to its momentum. A second μ^+ beam, whose polarization was reversed, was also developed. RHO requires only single track events in order to eliminate tracking ambiguities. The beam intensity was controlled by adjusting the slits along the beam line. The target was a circle made from two 10 mil mylar sheets glued together with a hole of 0.64 cm in diameter at the center. The target was placed normal to the beam and supported by a cylindrical plastic bag inflated with helium.

Although all eight MWPC chambers were installed and instrumented, only seven of them were used because dwarf 7 was unable to hold high voltage. The downstream cathodes of dwarf 3 had severe electronics feed-back oscillation problems and were also turned off. All the "live" chambers were operated at high voltages well on plateau, and the discriminator thresholds were adjusted to reasonable values. All scintillators were mounted, timed in and fully tested. In addition to the scintillator trigger, a "Snow White" trigger was constructed. This trigger

used the signals from the central region of the Snow White inner and outer cathodes. Data taken with the Snow White trigger will be used for determining the absolute efficiencies of the scintillators.

During six days of data taking, we were able to collect 2×10^8 trigger events under various conditions. Three modes of data were taken with scintillator triggers as well as with the Snow White trigger. The three modes distinguish themselves by the type of beam used and magnetic field values. Two of them were taken with the surface muon beam and magnetic field at 15 kG and 14.25 kG, respectively. For the third mode, the magnetic field was set at 15 kG and the beam was switched to that of reversed polarization. The three data sets will help check and understand systematic errors.

Figure 5. Four positron energy spectra for "one-loop" events, showing the current state of the analysis. The two upper spectra have the muons polarized upstream, while the lower spectra have the muons polarized downstream. The two spectra on the left represent muon decays upstream, while those on the right represent muon decays downstream. Note that the spectrometer acceptances are different in the two directions because of geometric differences.

After data taking was finished, the analysis immediately began. We first modified the track reconstruction program and updated the cuts used by it. Unfortunately, during last year's run electronics oscillations occurred frequently in some of the chambers. The reconstruction program was modified to extract these contaminated events. Following this, channel mapping and alignment were necessary. Helical track and cosmic ray events were used to verify the FASTBUS-to-detector-channel mapping of

the positron chambers and to check the alignment of the detector elements. Then both the internal alignment of the chambers themselves and the relative alignment between the chambers were examined. The first pass at anode alignment has been completed. With these alignment results implemented in the analysis, the energy resolution improved by about 100 KeV FWHM. Some typical current positron energy spectra are shown in Fig. 5. The cathode alignment is being studied at present.

Helical track data were used for scintillator alignment. By making adjustments in the geometry, the scintillator alignment was determined. The final offsets for the upstream and downstream scintillators were -0.0375 and -0.0449 radians, respectively.

The first task, following the completion of the channel mapping and the preliminary alignment, was locating the position of the target in z and obtaining the transverse beam spot at the target. The process of calculating the two were coupled together. First the target location was estimated by finding the centroid of the average z -coordinate of the two extrapolated points between the reconstructed track and the target bag. The transverse beam distribution described by (x,y) pairs was then given by the crossing point of the track at the target plane. If the target position was found correctly, then the beam spot would be the smallest because otherwise it would be "out of focus". To achieve this, the same procedure was repeated at different z 's away from the base z value described above. It was found that the smallest spot occurred at about $z = -1$ cm, i.e. the target was off center by 1 cm upstream in the Snow White coordinate system. This was confirmed by the asymmetric distribution of P_z , which is a sensitive quantity for the upstream and downstream acceptance.

Also scintillator and chamber efficiencies are being studied. The scintillator efficiency was obtained using the Snow White cathode trigger, magnet on data. Three types of data are available to determine the MWPC chamber efficiencies. They are: 1) magnet on data, 2) magnet off data, and 3) cosmic ray data. Efficiencies with all three data sets

are being studied, with one being checked against another. Preliminary results have been obtained only in the case of magnet on data.

We also studied the upper edge of the energy spectrum in attempting to determine both the centroid of the beam stopping distribution inside the target and the average magnetic fields upstream and downstream. Both of these effects influence the measured energy of the positron. The sharply falling edge of the spectrum at 52.8 MeV provides excellent sensitivity to them. The average centroid of the beam distribution in the target was 7.5 mil for the surface beam and 7.9 mil for the decay beam, both measured from the incident surface. Once the beam centroid is determined and the energy loss is accounted for, the average magnetic fields can be obtained by comparing the two edges between upstream and downstream for the same loop events.

To conclude, we think that the data taken last year are adequate to achieve $\delta\rho = 0.001$. However, additional problems, e.g. the location dependent electronics noise and the target offset, will increase the systematic uncertainties. We expect the overall systematic error to be < 0.0015 . Hence, a final precision of $\delta\rho = 0.002$ should be achieved.

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The $\bar{d}(x)/\bar{u}(x)$ Ratio in the Proton

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We are members of a new experiment at Fermilab, E866, which will determine the proton sea quark ratio:

$$\frac{\bar{d}(x) - \bar{u}(x)}{\bar{d}(x) + \bar{u}(x)} = \Delta_p(x) \quad (1)$$

via a high precision measurement of the relative Drell-Yan $\mu^+\mu^-$ pair yields in 800 GeV pp and pd collisions. $\Delta_p(x)$ will be determined to ± 0.015 over the range $0.03 < x < 0.15$ where we will be limited by the systematic uncertainties in the relative normalization. The experimental uncertainty will increase to ± 0.1 at $x = 0.3$, due to statistics. This experiment is motivated by the recent results of the NMC experiment¹ to study the Gottfried Sum Rule² (GSR) in deep inelastic electromagnetic scattering (DIS). They find:

$$\begin{aligned} \int_0^1 (F_2^{e,p}(x) - F_2^{e,n}(x)) dx/x &= \\ \frac{1}{3} - \frac{2}{3} \int_0^1 (\bar{d}_p(x) - \bar{u}_p(x)) dx &\quad (GSR) \\ \approx 0.240 \pm 0.016 &\quad (NMC \text{ result}) \end{aligned} \quad (2)$$

The GSR is based on the assumptions that the $u(x)$ and $d(x)$ quark structure functions of the proton and neutron obey charge symmetry (i.e., $u_p(x) = d_n(x)$, $\bar{u}_p(x) = \bar{d}_n(x)$, etc.) and that the strange and heavier quark flavors occur equally in the proton and neutron. Meanwhile the NMC result is based on the additional hypothesis that $F_2^{2n} \approx F_2^p + F_2^n$. Thus, it appears that there is a significant flavor asymmetry in the light sea quark distributions of the nucleon. This asymmetry is very hard to understand within a perturbative QCD model of the nucleon. Non-perturbative meson-cloud models naturally yield $\bar{d}_p > \bar{u}_p$ via $p \leftrightarrow n\pi^+$ and $n \leftrightarrow p\pi^-$, but they seem to be

unable to explain the magnitude of the observed effect.^{3,4}

The Drell-Yan mechanism, $q\bar{q} \rightarrow \text{virtual } \gamma \rightarrow \mu^+\mu^-$ within a hadronic medium, is an excellent probe of the anti-quark distributions in nuclei.³ The effective mass and longitudinal momentum of the virtual γ determine the quantities $x_b x_t$ and $x_b - x_t$, respectively, where $x_b(x_t)$ is the momentum fraction carried by the beam (target) parton. Valence quarks are far more likely to carry a significant fraction of a nucleon's momentum than sea quarks are, so $x_b - x_t > 0.2$ strongly favors the association of the quark in the Drell-Yan process with the beam and the anti-quark with the target. Thus, in a first-order approximation, proton-induced Drell-Yan on nuclear targets directly measures $\bar{u}(x_t)$ since $u_p > d_p$ and $\sigma(u\bar{u}) = 4\sigma(d\bar{d})$.

A previous Fermilab experiment, E772, investigated Drell-Yan production on d , C, Ca, Fe, and W to see if the A-dependent effects observed in DIS, the "EMC effect," were caused by sea quarks.⁵ Little or no modifications of the sea quark distributions were observed as a function of A except for "shadowing" in the region $x < 0.1$, which occurred at the same level as in DIS. By contrast, E772 found large A-dependent effects⁶ in the yields of J/ψ , ψ' and T . The results of E772 have recently been reanalyzed to extract $\Delta_p(x)$ by comparing the Drell-Yan yield from W to that from the isoscalar targets.⁷ No significant deviation of $\Delta_p(x)$ from zero was found, but the uncertainties are large because (N-Z)/A is only 0.2 for W and there are significant shadowing corrections that must be applied for such a heavy target.

E866, which is optimized to investigate $\Delta_p(x)$, is an extension of E772. Our choice of hydrogen and deuterium targets maximizes our sensitivity to $\Delta_p(x)$ while minimizing shadowing effects. We will use the same spectrometer system which was used by E772. It is shown in Figure 1. This, the Fermilab Meson East spectrometer, was originally built for Fermilab⁸ E605 and was used most recently by E789.

Several improvements were made during the course of E789, notably an increase in the data

acquisition system throughput by a factor of over 10 and an increase in the acceptance for low mass pairs. We will utilize these enhanced capabilities to obtain very high statistics for the low-mass $\mu^+\mu^-$ pairs that are needed to explore the region $x \sim 0.05$. These low-mass pairs will also let us see if shadowing persists in a system as light as deuterium. We will simultaneously obtain $> 10^7 J/\psi$, $> 10^5 \psi'$, and $> 2000 T$ to obtain their relative production cross sections in pp and pd . These are needed to predict dilepton yields at RHIC.

The E866 collaboration includes members from Abilene Christian University, Academia Sinica (Taiwan), California Institute of Technology, Fermilab, Los Alamos, Northern Illinois University, Oak Ridge, and our group at Texas A&M. The spokesman is Gerald Garvey from Los Alamos. The experiment received first-stage approval from the Fermilab PAC in December 1992. At that time, the PAC gave tentative approval of our full two month beam time request, and asked us to investigate the improvements that we could achieve either in acceptance range at low x or in statistics at high x by running longer. As of this writing, we expect to receive second-stage approval from the PAC at its next meeting and to run in either late 1994 or early 1995.

We expect to upgrade two major detector subsystems significantly for E866. The first is the data acquisition and run control computer. Although the E789 improvements imply that the data throughput to tape is now adequate for our needs, the on-line analysis capabilities are quite limited. A large contribution to the systematic normalization error comes from rate-dependent tracking inefficiencies. We estimate that we will need to analyze approximately 10% of our events in real time in order to monitor these effects adequately. We are currently investigating options to provide this capability. Meanwhile the primary run control computer is a PDP 11-45 that dates to the early days of E605 and is very difficult to maintain. We are considering replacing the PDP 11-45 at the same time as we upgrade the on-line analysis. The Los Alamos

Figure 1. Layout of spectrometer at FNAL.

and Cal Tech groups share the primary responsibility for the data acquisition system, but all groups, including ours, will be called upon to provide some software support.

Our group has the primary responsibility for the other major subsystem to be upgraded -- the hardware trigger. The trigger system for E772 consisted of a two-stage process of inspecting hit patterns in seven scintillator hodoscopes, four in the Y (bend) plane and three in the X (non-bend) plane, to identify candidate tracks. E605 and E789 also made extensive use of a custom-built third-stage parallel pipeline processor to see if wire chamber hit patterns confirmed the preliminary results from the scintillators. This third-stage processor was available for E772, but it was not used to veto any events. The bit pattern that it produced was recorded as part of each event, then was used in the on-line and quick first-pass off-line analyses to select potentially interesting events. But this procedure was found to introduce poorly understood systematic effects in the event reconstruction efficiency, so the final pass analysis disregarded it. The existing third-stage trigger configuration, that of E789, would require an extensive rebuild to meet the needs of E866. Given the experience of E772, the collaboration has

concluded that this rebuild would expend far more man-effort than justifiable.

The first two stages of the trigger logic consist of commercial NIM and CAMAC modules, plus a large number of custom-built units that are between 10 and 20 years old and poorly documented. The first stage decision looks for very simple coincidence patterns, primarily utilizing standard NIM modules. This configuration provides very little flexibility, together with a number of undesirable side-effects. Notably, it leads to an implicit p_T cut on the $\mu^+\mu^-$ pairs that rejects large p_T events. In parallel with the first-stage trigger, a number of custom-built modules, referred to as trigger matrices, study the hit patterns in hodoscopes Y1, Y2, and Y4 to identify triple-coincidences that represent candidate μ^+ or μ^- tracks that may originate from the target. This part of the trigger logic must be very flexible, since the patterns of interest at any given time depend on the effective masses of the virtual photons being studied and the currents in the three spectrometer magnets. The existing trigger matrices use fast ECL SRAM's that are downloaded via CAMAC to provide this flexibility. Unfortunately, they don't make a decision fast enough to provide input to the first-stage trigger decision.

The second-stage trigger is generated using a number of custom-built modules, many of which were fabricated at Nevis in the mid-1970's. It latches the outputs of the first-stage trigger logic and the trigger matrices. It then performs the necessary higher-order logic to select interesting events and pre-scaled diagnostic events to be recorded by the data acquisition system. The user defines the higher-order logic by inserting or removing modules from the system and selecting jumpers on these modules. Pre-scale factors are chosen in a similar way. This provides great flexibility to the user, but it also makes it far more difficult to know with certainty the current trigger configuration. This is crucial for a high precision experiment like E866. Furthermore, the second-level trigger logic was becoming unreliable during E789, and its age and documentation level make continuing maintenance even more difficult.

The above considerations have led us to the conclusion that the entire trigger system should be replaced if a suitable alternative can be identified. Ideally, we would like to replace the parallel systems of NIM logic and trigger matrices with a single integrated system that would simultaneously identify all of the logic patterns required for both diagnostic and physics triggers. Then a "master control circuit" would select the triggers of interest for any given run, together with their prescale factors. The front-end system must provide at least as much control over trigger patterns as the existing trigger matrices, and preferably more. The entire system should be configurable under computer control to facilitate automatic logging of its status at the beginning of each run and whenever changes are made. It must be able to cycle at the 53 MHz Fermilab beam repetition rate. Finally, since we only have $\sim 1\frac{1}{2}$ years until we need to be ready for beam, we have a practical constraint that most, if not all, of the system must consist of commercially available units.

At present, the option we are considering is to do the front-end processing in a set of new LeCroy 2366 CAMAC modules. This module consists of a Xilinx XC4005 or XC4006 field programmable gate array

(FPGA), together with 59 front-panel ECL-line-compatible connections, each of which may be set up as either an input or an output. The XC4006 FPGA includes 256 configurable logic blocks (CLB), each of which may be programmed to produce two arbitrary logic functions of four inputs each, one arbitrary logic function of five inputs, or selected logic functions of up to nine inputs. The actual logic performed by each CLB, together with the way the internal circuit paths interconnect the CLBs, is determined by the status of a set of $\approx 120k$ on-chip SRAM bits. LeCroy has designed the 2366 so that these SRAM configuration bits may be downloaded via CAMAC, providing a convenient way to change the actual logic functions performed whenever desired. Two such modules would be sufficient to replace the existing muon trigger matrices. Alternative configurations with four modules would be sufficient to identify muon tracks in Y1-Y2-Y4 or Y1-Y2-Y3-Y4, as desired, as well as hadron tracks in Y1-Y2-Y3. Two more modules would give us an X hodoscope track finder in parallel with the Y track finders. This would facilitate removing the existing constraints on p_T for $\mu^+\mu^-$ pairs. The major existing uncertainty is whether the XC4006 will be fast enough to cycle at the full 53 MHz beam rate. The logic functions themselves are more than fast enough, but we have not yet had an opportunity to determine the on-chip signal propagation delays. A potential contingency would be to bridge signals across pairs of modules, then cycle each member of the pair on alternate RF buckets. This would eliminate any worries regarding on-chip delays, but it may slow the overall trigger decision down too much. Furthermore, this would double the number of CAMAC modules, and thus cost, in the new system. We are currently trying to obtain the Xilinx FPGA simulation software to investigate these issues.

If we select LeCroy 2366's to replace the first-stage trigger NIM logic and trigger matrices, then we would probably build a custom printed circuit board to act as the master controller. This circuit would consist of standard series 10HK ECL integrated circuits, together with a few ECL PAL's to perform

the higher level logic functions that we require. We don't intend to begin serious work on this component until the front-end has been specified.

The next E866 collaboration meeting is to be held in mid-June. By that time, we should have received second-stage approval from the Fermilab PAC and should have a much better estimate of when we will be running. The various options for reconfiguring the trigger system will be discussed in detail, and a final choice will be made.

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Experimental Program in N-N, Few-N, and Kaon Physics

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and collaborators from several other institutions

A. Experiments at LAMPF (Clinton P. Anderson Meson Physics Facility)

1. Neutron-proton elastic spin-transfer from 485 to 788 MeV

This program (LAMPF experiment E876) was initiated in the summer of 1990 with measurements of the spin-transfer parameters K_{LL} , K_{LS} , K_{SL} and K_{SS} at 788 MeV, data which were published in 1991.¹ The experiment was completed in the summer of 1992, with measurements of these parameters at 485 and 635 MeV, and the results have since been published.² The results have a significant impact on the phase-shift analyses, providing sufficient data to over-determine the elastic N-N amplitudes near those energies. The experiment has been done in collaboration with scientists from Argonne National Laboratory (ANL), Los Alamos National Laboratory (LANL), Rice University (RiU), Rutgers University (RuU), the University of Central Arkansas (UCA), the University of Montana (UM), the University of Texas at Austin (UTA), and Washington State University (WSU).

These results will be complemented by additional measurements this summer in experiment E1293, in which the analyzing power for n-p elastic scattering for c.m. angles from 30° to 60° at 500, 650, 725 and 800 MeV with point to point uncertainty of 0.005 and overall normalization uncertainty of 2%. These measurements will extend our coverage to the c.m. angular range 30°-160°, which will include both the forward and backward peaks. This is of importance because the relative magnitude of the two peaks is a sensitive probe of the isospin-0 inelasticities. Joining us in this collaboration will be scientists from Louisiana Tech University, Boğaziçi University (Turkey), and Institut Ruder Bosković (Croatia).

2. Spin-transfer parameter $K_{LL}(0^\circ)$ for the $^2\text{H}(p,n)2p$ reaction from 305 to 788 MeV

The spin-transfer measurements of E876 revealed a 10-16% normalization discrepancy with previous measurements of the polarization of the LAMPF neutron beam. This led to a new proposal (E1234), to remeasure the $^2\text{H}(p,n)2p$ spin-transfer parameter $K_{LL}(0^\circ)$ at beam energies of 305, 485, 635, 722 and

788 MeV. The results confirmed the need for renormalization of the earlier data, and were published during the past year.³ The collaboration was the same as that in E876, with the addition of another collaborator from the University of Colorado.

3. Single-pion production in np scattering (LAMPF E1097)

Considerable effort was spent on the development of apparatus for this experiment during the past few years. Unfortunately, because of serious budgetary problems at LAMPF, approval of the experiment was withdrawn late in 1992.

4. Absolute pp-elastic differential cross sections from 492 to 793 MeV

Measurements were made for the c.m. angular region 30° - 90° at incident energies 492, 576, 642, 728 and 793 MeV. A total uncertainty of less than 1% was made possible by particle-counting for beam normalization and extensive cross-checking for systematic effects. The new data are consistent with previous results above 600 MeV, but have uncertainties reduced by a factor of ~ 10 . Near 500 MeV the results are consistent with 90° data from TRIUMF, but differ significantly from similar data from PSI. The work was done in collaboration with people from LANL, UCLA, RiU, RuU and UTA, and served as the basis for the dissertation research of A. J. Simon, who obtained the PhD degree in May 1993. A manuscript presenting these results for publication is in preparation.

5. Absolute differential cross section measurements for the $p+p \rightarrow \pi^+ + d$ reaction for energies 500-800 MeV

As a necessary by-product of the preceding experiment, absolute determinations of the differential cross section for the $pp \rightarrow \pi^+ d$ reaction of high accuracy were also made. These results have been published.⁴

6. Measurements of np elastic spin-correlation parameters between 500 and 800 MeV

In this earlier experiment, the parameters C_{SL} and C_{LL} for backward c.m. angles, and the parameters C_{SS} and C_{LS} for forward c.m. angles were measured for various energies between 484 and 788 MeV. Collaborators included persons from ANL, New Mexico State University, LANL, UM and WSU. These results have now been published.^{5,6}

7. Measurement of the p-p elastic spin-correlation parameters A_{LL} and A_{SL} between 500 and 800 MeV

The results of this earlier set of measurements have now been published.⁷

8. Measurement of the forward-angle analyzing power in pn and pp quasifree scattering at 643 and 797 MeV

The results of this earlier experiment also were published during the past year.⁸

9. Differential cross section for n-p elastic scattering at 459 MeV

The data of this experiment, also obtained earlier, have now been published.⁹ This work was done in collaboration with workers from LANL and UTA.

10. Earlier LAMPF experiments

In an earlier LAMPF experiment, the spin-correlation parameter A_{NN} for n-p elastic scattering was measured for energies between 300 and 665 MeV. A manuscript presenting these results is nearing completion.

B. Kaon Experiment at Brookhaven National Laboratory (BNL)

Collaborators in this experiment included personnel from Tel Aviv University, BNL, Vassar College, Osaka University and TRIUMF. The final results of the experiment, measurements of the K^+ total cross sections for various target nuclei as a test for nucleon "swelling", have now been published.¹⁰

C. Experiment at KEK (National Laboratory for High Energy Physics, Tsukuba, Japan): Measurement of the energy dependence of the analyzing power for the $pp \rightarrow pp$ and $pp \rightarrow d\pi^+$ for energies in the region 500-800 MeV

Participating institutions in this collaboration included KEK, Kyoto University, Tohoku University, and the Tokyo Institute of Technology. The results obtained for the $pp \rightarrow d\pi^+$ have been published,¹¹ and a manuscript presenting the final results of the $pp \rightarrow pp$ measurements has been submitted for publication.¹²

D. Other experiments at LAMPF and BNL.

These miscellaneous results have also been published.

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NUCLEAR THEORY

Nuclear Structure Study of the Odd-A Tc Isotopes

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We reported the preliminary result for the positive parity states along with the detail discussion of this model last year.¹ We re-examined the results for the positive parity energy spectra by adjusting the exchange interaction. This modification slightly affected the spectra given in the previous progress report with a larger effect on the B(E2) values (not reported previously). We present in the following the corrected results for the positive parity energy levels as well as the negative parity states and the B(E2) values.

We have investigated the odd-A Tc isotopes in the mass $A=100$ region within the neutron-proton interacting boson-fermion model (IBFM-2).² The calculation is based on the validity of the $Z=38$ subshell closure. The results for the energy spectra and electromagnetic transitions are compared with experimental data and with results from other calculations which considered $Z=50$ as a valid closed shell for Tc isotopes.

All of the previous theoretical calculations,^{3,4} IBFM-1 and IBFM-2, of the odd-A Tc isotopes were performed before our experimental data on ^{101}Tc was available.⁵ Moreover, the neighboring even-even Ru isotopes are chosen as a core for Tc isotopes in these calculations. The comparison of the energy levels of the odd-A Tc isotopes with neighboring even-even Mo isotopes indicated that Mo isotopes are the proper core for these nuclei.

In this work we will use the IBFM-2 approach to explore the validity of the $Z=38$ subshell closure and the configuration dependent deformation in odd-A Tc isotopes. It will be shown, that the shape change in the Tc isotopes is similar to that of the Mo isotopes rather than the Ru isotopes. This implies that the shape transition is from vibrational (U(5) limit) to rotational (SU(3)) limit, rather than to the O(6) limit (γ unstable). In this report, we present the results of the first systematic calculations performed using the proton-neutron interacting boson-fermion model⁶ with

$Z=38$ as a valid subshell closure. Therefore, the states of the odd-A Tc isotopes can be considered as proton-particle states.

Figure 1. Comparison of the excitation energy of the first excited state in the even-even Mo core with the excitation energy of the centroid of the multiplet for positive and negative band of odd-A Tc isotopes as a function of neutron number.

The parameters for the core Hamiltonian are given in Table I. These parameters are taken from a previous IBM-2 investigation⁷ of the even-even Mo isotopes in which $Z=38$ and $N=50$ were taken as proton and neutron closed shells, respectively. In the proton 20-50 major shell, there are five single-particle orbits, four with the negative parity ($1f_{7/2}$, $1f_{5/2}$, $2p_{3/2}$, $2p_{1/2}$) and one with the positive parity ($1g_{9/2}$). For the nuclei with the number of protons larger than 40 the $2d_{5/2}$ orbit from the upper shell comes low in energy. Therefore, it is energetically possible for the particle to occupy this orbit. Thus, for the odd-A Tc isotopes the positive parity single-particle orbits are taken to be $1g_{9/2}$ and $2d_{5/2}$. We investigated the effect of the $2d_{5/2}$ orbit on the energy and electromagnetic transitions which will be discussed later. In Table II, we list the single-

Table I. IBM-2 parameters for even-even Mo isotopes taken from Ref. [7].

N	N_ν	ϵ_π	ϵ_ν	κ	χ_π	χ_ν			
54	2	1.10	0.740	-0.090	0.4	-1.2	-0.50	0.10	0.00
56	3	1.25	0.750	-0.078	0.4	-1.2	-1.00	0.45	0.06
58	4	0.81	0.595	-0.060	-0.4	-1.2	-0.55	0.18	0.12
60	5	0.60	0.510	-0.080	-0.4	-1.0	-0.22	0.07	0.12

^aAll the parameters are in MeV except for χ_π and χ_ν , which are dimensionless.

^bIn these calculations the authors used $N_\pi=2$ and Majorana parameters of $\xi_{1,3}=0.035$ MeV, and $\xi_2=0.08$ MeV.

Table II. Results from BCS calculation for the orbitals involved, along with single particle energies used in present calculations.

nlj	$\epsilon_j(\text{MeV})$	$E_j(\text{MeV})$	v_j^2
$2p_{1/2}$	2.10	1.49	0.79
$2p_{3/2}$	0.35	2.87	0.95
$1f_{5/2}$	0.90	2.39	0.93
$1f_{7/2}$	-3.20	6.27	0.99
$1g_{9/2}$	3.20	1.24	0.40
$2d_{5/2}$	7.20	4.42	0.02

Table III. Boson-Fermion interaction parameters for both positive- and negative-parity states of Tc isotopes.

Parity	A_π	Γ_π	Λ_π	Orbitals
+	-0.10	0.87	-4.0	$1g_{9/2}, 2d_{5/2}$
-	-0.40	0.00	2.5	$1f_{7/2}, 2p_{3/2}$ $1f_{5/2}, 2p_{3/2}$

^aAll parameters are in MeV.

particle energies, ϵ_j , quasiparticle energies, E_j , and occupation probabilities, v_j^2 , used in this calculation.

The parameters for boson-fermion Hamiltonian for positive and negative parity states are given in Table III. The parameters are kept constant for each band except for the parameter A_π of the negative parity band of ^{97}Tc where we used the value of $A_\pi = -0.13$ MeV. The simplest version of the core-particle coupling (CPC) model predicts that the energy of the centroid of multiplets, resulted from coupling of the single-particle with an excited state of

the even-even core, should be equal to that of the corresponding core state,⁸ if the monopole-monopole interaction vanishes. Therefore, the monopole interaction strength can be extracted for each nucleus from energy differences between the $E_{2_1^-}$ state of the even-even Mo core and the centroid of the corresponding multiplets, resulting from $2_1^+ \otimes 9/2^+$ or $2_1^+ \otimes 1/2^-$. Using the available experimental data for the excited states of the Mo and Tc isotopes, we have obtained the values $A_\pi = -0.12$, and -0.23 MeV for the positive parity states of ^{97}Tc , and ^{99}Tc , respectively. The corresponding values for the negative parity states are $A_\pi = -0.25$, -0.36 , and -0.39 MeV for ^{97}Tc , ^{99}Tc , and ^{101}Tc , respectively. In Figure 1 we have plotted the excitation energy of the first 2^+ state of the even-even Mo core along with centroid energy of the multiplets for both positive and negative parity states. We note that the value of the A_π depends on the parity of the states and mass number. Although these values differ from one isotopes to the next it is seen from Figure 1 that assuming a constant value for A_π is a reasonable approximation. We therefore, looked for a description of the excited states of the positive-parity odd-A Tc isotopes using the same value for the parameter A_π . Another constant value was assumed for the negative parity states. The other parameters, Γ_π and Λ_π , were also kept constant, albeit smooth changes in A_π and Λ_π would improve the theoretical prediction. The structure coefficients χ_ρ ($\rho = \pi, \nu$) in the boson quadrupole operator have the same values as in the corresponding even-even Mo core nuclei. In the present calculations, we first

diagonalized the core Hamiltonian, using the parameters given in Table I, and then truncate the number of core states. The truncation was carried out by retaining the core states below 4 MeV before coupling the single-particle state of the odd-nucleon.

Figure 2. Excitation energy of the positive parity levels of odd-A Tc isotopes. The experimental data are taken from Refs. [5].

In Figure 2 we have plotted the experimental excitation energy of the positive-parity levels of 97-103Tc isotopes along with the calculated values within the IBFM-2 using the parameters given in Table III. The solid lines are the calculated excitation energies for $9/2^+$, $5/2^+$, $13/2^+$, and $17/2^+$ states and dashed lines are the calculated energies for $7/2^+$, $11/2^+$, and $15/2^+$ states. The experimental energies are given by points representing different angular momenta. The overall agreement between experimental and calculated values is good. It is interesting to note that our calculation reproduces well the experimental data for the three low-lying levels with $J^\pi = 9/2^+$, $7/2^+$, and $5/2^+$. This is a significant improvement over previous results of Refs. [3,4], especially for ^{101}Tc . The calculated excitation energy for the $11/2^+$ level of ^{101}Tc is greater than the $13/2^+$ excitation energy in contrast with the experimental data. However, the deviations of the experimental and calculated values for these two levels are not large.

Figure 3. Occupation number for the $1g_{9/2}$ and the $2d_{5/2}$ orbitals in the first excited states $J^\pi = 5/2^+$, and $9/2^+$.

In Figure 3 we show the calculated occupation numbers of the $1g_{9/2}$ and $2d_{5/2}$ orbits for the first excited states with $J^\pi = 5/2^+$, and $9/2^+$ as a function of neutron number for Tc isotopes. The data for this figure is a result of best fit for Tc isotopes when considering both $1g_{9/2}$ and $2d_{5/2}$ orbitals. As seen in Figure 3, the occupation number for the $2d_{5/2}$ orbit may be as large as 10%. For example, as shown in Figure 3, the $5/2^+$ level have a non-negligible $2d_{5/2}$ component which leads to a large deviation in excitation energy between theory and experimental data when only the $1g_{9/2}$ orbit was considered. It is found that for such states, it was not possible to obtain reasonable excitation energies if one considers only $1g_{9/2}$ orbit in IBFM-2 calculation for positive parity states of the Tc isotopes. The $2d_{5/2}$ presence is even more crucial in calculating the electromagnetic transitions. Since we reported the results of our calculations for the positive parity band previously we will not discuss the positive parity states any further.

Our calculation shows that for an excitation energy less than one MeV, the $1/2^-$ excited states are predominantly $p_{1/2}$ proton states. Our investigation shows that the value of Γ_π is practically zero for the negative parity states.

Figure 4. Excitation energy of the negative parity levels of odd-A Tc isotopes. The experimental data are taken from Ref. [5].

In Figure 4 we present the experimental result for the negative parity states for $^{97-103}\text{Tc}$ isotopes along with the result of the calculation using the parameters given in Table III. Note, that for ^{97}Tc we have used the value $A_\pi = -0.13$ MeV. The overall agreement between the experimental and calculated values is reasonable. For $^{97,99}\text{Tc}$ the states with $J^\pi = 7/2^-$, $11/2^-$, and $15/2^-$ have not been observed. In ^{101}Tc , the calculated results for low-lying levels are in very good agreement with experimental data. However, the calculated values for $13/2^-$, and $17/2^-$ deviate from experimental results of Ref. [5]. In Ref. [5] the spin assignment was based on the in-plane/out-of-plane anisotropy measurement. As it was mentioned in Ref. [5], no valid anisotropy could be measured for the 224 keV transition. Therefore, the assignment of $7/2^-$ to the energy level at 619 keV is purely speculative. If we assign a $J^\pi = 9/2^-$ to this energy level, the energy levels at 947- and 1500 keV should have $J^\pi = 13/2^-$, and $17/2^-$, respectively, instead of $11/2^-$ and $15/2^-$. Our theoretical calculations strongly support the spin assignment of $9/2^-$, $13/2^-$, and $17/2^-$ to levels at 619, 947 and 1500 keV, respectively. It is

clear that more experimental data, especially some angular distribution measurements, are needed for this neutron-rich Tc isotopes.

We calculated transition probabilities for the Tc isotopes and compared the results with known electromagnetic transition data.^{9,10} Within the proton-neutron interacting boson-fermion model the electromagnetic quadrupole, E2 operator for odd-A proton nuclei, can be written:

$$T^{(E2)} = T_B^{(E2)} + T_{F,\pi}^{(E2)} \quad (1)$$

$T_B^{(E2)}$ is the collective (boson) part of the E2 operator and is given as:

$$T_B^{(E2)} = e_{B,\pi} Q_\pi^2 + e_{B,\nu} Q_\nu^2, \quad (2)$$

where $e_{B,\pi}$ ($e_{B,\nu}$) is the proton (neutron) boson effective charge and Q_ρ^2 are the usual boson quadrupole operators as given in Ref. [2].

The single-particle part of the E2 operator is given by:

$$T_{F,\pi}^{(E2)} = e_{F,\pi} \sum_{jj'} e_{jj'}^{(2)} (a_j^\dagger \times \tilde{a}_{j'})^{(2)}, \quad (3)$$

where $e_{F,\pi} = e$. The coefficients $e_{jj'}^{(2)}$ are related to the single-particle matrix elements of the E2 operator by:

$$e_{jj'}^{(2)} = -\sqrt{\frac{1}{5}} \left\langle l \frac{1}{2} j \right| r^2 Y^{(2)} \left| l' \frac{1}{2} j' \right\rangle (u_j v_{j'} - v_j u_{j'}). \quad (4)$$

The factor $(u_j v_{j'} - v_j u_{j'})$ takes into account the quasi-particle nature of the single-particle state.

The B(M1) transition strength and magnetic moment are sensitive to contributions from the odd-particle. Within the IBFM-2 the M1 transition operator can be written as follows:

$$T^{(M1)} = T_B^{(M1)} + T_{F,\pi}^{(M1)}. \quad (5)$$

with the boson part of the operator given by:

$$T_B^{(M1)} = \sqrt{\frac{3}{4\pi}} (g_\pi \sqrt{10} (d_\pi^\dagger \times \tilde{d}_\pi)^{(1)} + g_\nu \sqrt{10} (d_\nu^\dagger \times \tilde{d}_\nu)^{(1)}), \quad (6)$$

where the coefficient g_π (g_ν) is the proton (neutron)

boson g-factor. The single-particle part of the M1 operator, $T_{F,\pi}^{(M1)}$ is given by:

$$T_{F,\pi}^{(M1)} = \sqrt{\frac{3}{4\pi}} \sum_{jj'} e_{jj'}^{(1)} \langle a_j^\dagger \times \bar{a}_{j'} \rangle_\pi^{(1)}, \quad (7)$$

where

$$e_{jj'}^{(1)} = -\sqrt{\frac{1}{3}} \left\langle l \frac{1}{2} j \left| g_l l + g_s \frac{1}{2} j \right| l' \frac{1}{2} j' \right\rangle \delta_{ll'}. \quad (8)$$

The coefficient g_l and g_s are the single-particle g-factors of the odd particle. For a detailed discussion of the electromagnetic transition within the IBFM-2, see Ref. [6].

In our calculation the boson effective charge $e_{B,\pi}$ and $e_{B,\nu}$ are taken from previous study of the E2 transition for the even-even core,⁷ $e_{B,\pi} = e_{B,\nu} = 0.106$ eb.

With the exception of a few isotopes, experimental data on electromagnetic transitions is rather scarce. Therefore we have restricted our discussion to known data and some general characteristics of the E2 transitions as a function of the neutron number. For the positive parity states we have shown the $B(E2; 13/2_1^+ \rightarrow 9/2_1^+)$ in Fig. 5(a) as a function of neutron number. In this case $B(E2)$ values increase as a function of neutron number. This is similar to the behaviour of the $B(E2; 2_1^+ \rightarrow 0_1^+)$ in the corresponding Mo nuclei.⁷ In Fig. 5(b) we have shown the result of the $B(E2; 5/2_1^- \rightarrow 1/2_1^-)$ for the negative parity band as a function of neutron number. In Table IV the known electromagnetic transition for ⁹⁹Tc from Refs. [10, 11] has been compared with the calculated result. The overall agreement between the calculated and experimental data is reasonable, within the experimental error bars. In Figure 6(a) the quadrupole of the first and second excited states of odd-A Tc isotopes are plotted as a function of neutron number. The quadrupole moments of the $5/2_1^+$ and $7/2_1^+$ states are very different from quadrupole moment, Q_{2_1} of the even-even Mo core.¹² In Fig. 6(b) the quadrupole moments of the $3/2_1^-$ and $5/2_1^-$ states are plotted as

a function of neutron number. The quadrupole moments of the first and second excited states of the negative parity band have a similar behaviour to the Q_{2_1} of the even-even Mo isotopes.

Figure 5. (a) $B(E2; 13/2_1^+ \rightarrow 9/2_1^+)$ values in odd-A Tc isotopes. The experimental data are taken from Ref. [10]. (b) $B(E2; 5/2_1^- \rightarrow 1/2_1^-)$ values of odd-A TC isotopes.

We have carried out a systematic investigation of the odd-A Tc isotopes in the framework of the IBFM-2 for both positive and negative parity states. The calculated energy spectra and electromagnetic properties have been compared with the experimental data. The results are in good agreement with the experimental data. We have also clarified the spin assignments of energy levels in ¹⁰¹Tc. We have

presented an alternative description for the odd-A Tc isotopes within the IBFM-2 framework. We have taken the Mo isotopes as a core with $Z=38$ as a valid subshell closure and $\epsilon_\pi \neq \epsilon_p$. We have investigated the effect of the $2d_{5/2}$ orbit which is associated with the major shell above the valence shell. It was shown that the presence of this orbit is important even for energy level calculations.

Table IV. Comparison of experimental and theoretical electromagnetic transition of the positive-parity states of ^{99}Tc .

		$B(E2; J_i \rightarrow J_f)(e^2b^2)$	
J_i^π	J_f^π	Exp	Theory
$7/2^+$	$9/2^+$	0.10(2)	0.038
$5/2^+$	$9/2^+$	0.024(9)	0.107
$11/2^+$	$9/2^+$	0.076(11)	0.099
$13/2^+$	$9/2^+$	0.133(19)	0.080
$5/2^+$	$9/2^+$	0.018(3)	0.001
$9/2^+$	$9/2^+$	0.001(4)	0.002

Figure 6. (a) $Q_{7/2_1^+}$ and $Q_{5/2_1^+}$ of odd-A Tc isotopes.

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(b) $Q_{3/2_1^-}$ and $Q_{5/2_1^-}$ of odd-A Tc isotopes.

Investigation of Even-Even Kr Isotopes Within IBM-2 Framework

H. Dejbakhsh, A. Kolomiets, and S. Shlomo

The light Kr isotopes lie in a transitional neutron-deficient mass $A = 70$ -80 region where a strong variation of collective properties has been observed as a function of both neutron and proton numbers.¹ The Kr isotopes have been studied extensively in the past decade because these nuclei were among the first in this mass region which revealed large quadrupole deformations, coexistence of different shapes and triaxiality.²

The origin of the large deformation and shape coexistence in this region is partially due to the existence of subshell closure at $Z=38$ and $N=38$. The Strutinsky-Bogolyubov calculations of Refs. [3] and [4] predict stable deformation and disappearance of shape coexistence away from $Z=N=38$ in this mass region as well as shape transitions from prolate to oblate deformation in light Kr isotopes.

It was shown that the light Kr isotopes (^{74}Kr , ^{76}Kr) have a large ground state deformation which coexists with nearly spherical 0_2^+ levels.² Further investigation concluded⁵ that ^{72}Kr ($N=Z$) has an oblate ground state which interacts with a strong prolate 0_2^+ band. This conclusion is in accord with the result obtained by Nazarewicz *et al.*³

The Kr isotopes with the neutron number, N , close to $N=39$ (half-filled neutron shell) exhibit a highly deformed rotational band coexisting with nearly spherical states of similar energies. For the Kr isotopes maximum deformation is reached at midshell. Note that the even-even Kr isotopes closest to midshell are ^{74}Kr ($N=38$) and ^{76}Kr ($N=40$). Although these two isotopes would be equally deformed if shell occupancy were the only factor involved, experimental data suggest that ^{76}Kr is somewhat more deformed, see Figures 1 and 2. In Figure 1 experimental energy levels of the yrast band are plotted as a function of the neutron number for $^{72-84}\text{Kr}$. The experimental values are shown with different symbols for different angular momenta.

The dashed lines connect the experimental points to guide the eyes.

Figure 1. Experimental and calculated energy levels of yrast band in $^{72-84}\text{Kr}$.

In Fig. 2a we have plotted the excitation energies of the first 2_1^+ state, $E_{2_1^+}$, for $^{72-84}\text{Kr}$ as a function of $N_n \cdot N_p$ and $N_\nu \cdot N_\pi$, where N_n , N_p , N_ν , and N_π are the number of valence neutrons, valence protons, neutron bosons, and proton bosons, respectively. Similarly in Fig. 2b we have plotted the

$E_{4_1^+}/E_{2_1^+}$ ratio as a function of the $N_n \cdot N_p$ and $N_\nu \cdot N_\pi$. The dashed lines in Figs. 2a, and 2b are drawn to guide the eyes.

The even-even Kr isotopes, $^{74-82}\text{Kr}$, were investigated within the Interacting Boson Model 2 (IBM-2)⁶ more than a decade ago. A detailed description of this model can be found elsewhere.⁷ In this investigation it seems that the authors mainly concentrated on yrast transitions. The calculated energies of the excited zero (0_2^+) and 2_2^+ states deviate largely from the known experimental values, see Ref. [6]. Since this investigation, a large amount of new experimental data on energy levels and

transition strengths of even-even $^{74-84}\text{Kr}$ isotopes, and in particular, the experimental data on energy levels of ^{72}Kr ($N=Z=36$) have become available.

Figure 2. a) Systematic of $E_{4_1^+}$. b) Systematic of $E_{4_1^+}/E_{2_1^+}$ for Kr isotopes. Data points are shown as symbols, the dotted lines are drawn to guide the eyes.

In a recent life-time measurement⁸ of the 0_2^+ state in ^{80}Kr , the authors compared the experimental results of the low lying positive states with the calculated values of IBM-2. These authors⁸ carried out IBM-2

calculations only for $^{78-82}\text{Kr}$, paying special attention to 0_2^+ , 2_2^+ , and 2_3^+ states. Their results are in better agreement with experimental data than are the results of Ref. [6].

Our main goal of this investigation is to extend the IBM-2 calculation of even-even Kr isotopes from $A=72$ to 84. This broader systematic study enables us to investigate the midshell effect associated with shape change. We pay special attention to excited 0_2^+ , 2_2^+ , 2_3^+ , and 3_1^+ states in addition to yrast states. We also calculate the $B(E2)$ values and the $B(E2)$ ratios for all known data. We attempt to find the correlation between the IBM-2 parameters with shape changes in these nuclei. We do these by taking the following steps:

1. We investigate even-even Kr isotopes in the IBM-2 framework assuming that the single particle energies of the neutron boson and proton boson are the same, $\epsilon = \epsilon_\pi = \epsilon_\nu$. This is similar to the approach of the Refs [6] and [8].
2. We investigate the Kr isotopes as above but taking $\epsilon_\pi \neq \epsilon_\nu$, similar to the approach of Ref. [9].
3. In order to investigate shape coexistence we plan to apply IBM-2 configuration mixing to these nuclei for further insight into the shape coexistence.

Z and $N=28$ and 50 were taken as proper proton and neutron closed shell for these nuclei. In the first calculation we started with the parameters listed in Ref. [8]. This set of parameters could not provide satisfactory results for the broader range of nuclei we are investigating.

Parts 1 and 2 of our investigation have been completed. In this report we only discuss the result of the first calculation. The parameters for this calculation are given in Table I. The result of the energy level calculation is shown in Fig. 1 along with the experimental data, the solid lines are the result of this calculation. The calculated values are in good agreement with experimental data. We predict the general trend of the experimental energy levels by varying only two parameters, ϵ and χ_π , the other parameters were kept constant. The result for

B(E2)'s are shown in Fig. 3. The experimental data are shown as solid circles and a dashed line connects the data points, the solid line is the result of this calculation. The agreement between the experimental and calculated values is good. We will continue the investigation of even-even Kr isotopes further in order to shed some light on the direction of the shape transition for these nuclei. The other parts of this project are still under investigation.

Figure 3. Experimental and calculated B(E2)'s of even-even Kr isotopes.

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Table 1. IBM-2 parameters for even-even Kr isotopes.

N	N _{ν}	ϵ	κ	χ_{π}	χ_{ν}	$\omega_{\nu\nu}$	$\omega_{\nu\pi}$
36	4	0.920	0.08	-0.1	-0.3	0.000	0.000
38	5	0.765	0.08	-0.8	-1.2	0.025	0.025
40	5	0.745	0.08	-0.8	-1.2	0.025	0.025
42	4	0.755	0.08	-0.5	-1.2	0.025	0.025
44	3	0.840	0.08	0.1	-1.2	0.025	0.025
46	2	0.945	0.08	-0.1	-1.2	0.025	0.025
48	1	1.000	0.08	-0.1	-0.3	0.025	0.025

^a All the parameters are in MeV except for χ_{π} and χ_{ν} which are dimensionless.

^b In these calculations we used N _{π} = 4 and Majorana parameters of $\xi_3=0.27$ MeV and $\xi_2=0.055$ MeV.

Single Particle Level Density in the Continuum

S. Shlomo and H. Dejbakhsh

One of the most interesting experimental results in heavy-ion reactions, first seen at our laboratory, is the sharp decrease of the level density parameter a with temperature T (excitation energy). It was found that a decreases from $A/8$ at $T \leq 3$ MeV to $A/14$ at $T = 5$ MeV. To provide a theoretical explanation, we have developed¹ a model which simultaneously includes, in a realistic way, many important effects: (a) surface diffuseness, (2) continuum, (3) space variation of the momentum and the frequency dependent (m_k and m_ω) effective masses, and (4) shell effects. The temperature dependence of these effects and of the mean field is also accounted for by the model. Using this model, which represents an advance in the state of the art, we have also calculated² the mass and temperature dependence of a .

It has been recognized that the single particle level density $g(E)$ should be calculated using a finite potential well, since an accurate treatment of the continuum is very important. Considering a Wood-Saxon potential well for a heavy nucleus ($A=274$), we have carried out³ accurate numerical calculations of $g(E)$ applying the methods: (i) Green's function approach, (ii) phase shift (derivative) approach, and (iii) Thomas-Fermi approximation. It is worthwhile to note the following:

1. To determine the accuracy and the advantages or disadvantages of these methods, we examined the corresponding results for a fixed orbital angular momentum, L , up to $L \sim 50$. The results for $g(E)$ are obtained by taking the sum over L to a certain maximum value of L . We have also calculated the corresponding smooth single particle level density using the Strutinski method. We point out that the occurrence of a sharp resonance, such as the $L=8$ resonance which has a width of less than 5 eV in our calculations, is a numerical problem for the phase shift (derivative) approach.
2. For an energy independent potential well, the resulting quantum mechanical (smooth) single particle

level density, obtained using the Green's function and phase shift methods, agrees well with the semi-classical result of the Thomas-Fermi approximation. When summed over all L , the level density is positive for all values of E . This result is not in contradiction with Levinson's theorem. In fact, for a fixed L , the corresponding single particle level density is negative for large E and fulfills the requirement of Levinson's theorem.

3. For an energy-dependent potential, deduced from nucleon-nucleus scattering, $g(E)$ is significantly different from that due to an energy independent potential. Decreasing the magnitude of the potential depths by $0.3 \cdot E$, we find that the calculated $g(E)$ by the phase shift approach becomes negative for $E > 40$ MeV. For the Green's function and the Thomas-Fermi methods, $g(E) > 0$ for an attractive potential well. This disagreement can be easily understood by noting that the phase shift is directly related to the number of states where the Green's function is related to the level density. We have modified the Thomas-Fermi and the Green's function expressions to reproduce the single particle level density.

4. It is important to point out that the local density approximation (LDA), in which a is directly given in terms of the integral of $\rho^{1/3}$, where ρ is the matter density, is quite often used in the literature (in heavy ion collisions) to relate excitation energy and temperature. Our investigation showed that this LDA approach overestimates⁴ a by almost a factor of 2.

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Light Front Dynamics and the Binding Correction

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It has been shown¹ that the binding correction in deep inelastic lepton scattering can explain the bulk of the nuclear EMC-effect at $x \geq 0.2$. This result has significantly restricted searches for the possible contribution of more exotic effects. However, in some later papers² it was claimed that the binding correction is unimportant if the light front (LF) representation is used instead of the instant form (IF) representation.

In the present work, it is shown that the nuclear binding correction in deep inelastic scattering is essentially independent of the adopted representation. To prove it, we have used the LF representation, as in Ref. [2], and compared the result to the earlier results based on the IF representation.

In the LF representation, the nuclear structure function is completely determined by the LF momentum P_+ of a struck nucleon. This component of the momentum is strictly conserved and well defined in the LF representation. Therefore for P_+ of a struck nucleon, we may use the following equation

$$p_+ = P_+^A - P_+^{A-1} \approx m_N - E_{sep} \quad (1)$$

where P_+^A and P_+^{A-1} are the LF momenta of the initial and residual nuclei and E_{sep} is the average nucleon separation energy. The crucial point to obtain (1) is that the initial and residual nuclei are the free localizable systems, and therefore their LF momenta are trivially related to the usual momenta.

The authors of Ref. [2], instead of using the conservation of the momentum P_+ , have used the sum rule for the nucleon LF momenta

$$\int d\underline{p} \rho(\underline{p}) p_+ = P_+^A / A \quad (2)$$

where $\underline{p} = (p_+, p_1, p_2)$ and $\rho(\underline{p})$ is the nucleon LF momentum distribution. But the sum rule (2) is not exact without the contribution of other constituents (mesons). The part of the binding correction that was not included in the results of the Ref. [2] is the measure of the violation of the sum rule (2) by non-nucleonic constituents.

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Formation and Decay of Toroidal and Bubble Nuclei and the Nuclear Equation of State

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Based on the Boltzmann-Nordheim-Vlasov calculations, Moretto *et al.* recently observed multifragmentation following the formation of nuclear "disks" for Mo+Mo collisions.¹ They argued that such multifragmentation was due to surface instabilities of the Rayleigh-Taylor kind. On the other hand, subsequent calculations^{2,3,4,5} based on similar models predicted bubble and/or toroidal geometries, analogous to those studied by C.Y. Wong⁶ some time ago.

To investigate the dependence on the equation of state (EOS) and to look for experimental observables, we have performed improved BUU calculations⁵ for $^{92}\text{Mo} + ^{92}\text{Mo}$ collisions. In our calculations, we have included Coulomb interactions and have used a Lattice Hamiltonian method⁷ to propagate test particles. This method provides a reasonable nuclear surface and accurate energy conservation. For details of this model, see Refs. 5 and 8.

In Figure 1, we display, respectively, the top and front views of the BUU calculations for $^{92}\text{Mo} + ^{92}\text{Mo}$ collisions at $b=0$ and $E/A = 85$ MeV calculated with the stiff EOS (nuclear compressibility $K=375$ MeV). Clearly, due to the early compression and subsequent expansion, a metastable torus is gradually formed with its normal axis parallel to the beam direction. This torus eventually breaks up simultaneously, though slowly, into fragments of nearly-equal sizes with their radii approximately equal to the minor radius⁶ of the torus at breakup. In our study,⁵ we find that as the incident energy is increased, a torus with a larger aspect ratio⁶ is formed which subsequently breaks up into a larger number of fragments. This result is consistent with calculations within the liquid-drop model.⁹

In contrast, in the calculations with the soft EOS shown in Fig. 2, a nuclear bubble starts to emerge when the system expands to its maximum at $t \approx 60$ fm/c. Similar to the formation of a torus, the inner surface of the bubble starts from zero and continues

$^{92}\text{Mo} + ^{92}\text{Mo}$, $E/A=85$ MeV, $b=0$, Stiff EOS

Figure 1 BUU calculations with the stiff EOS for $^{92}\text{Mo} + ^{92}\text{Mo}$ collisions at $E/A = 85$ MeV, $b=0$. Only areas with densities $\rho \geq 0.1\rho_0$ are shown. Scales between ticks are 10 fm.

to increase while the outer surface remains relatively unchanged. This bubble stays for $t \approx 60$ fm/c and then breaks up simultaneously into several fragments (fragments are emitted isotropically).

To guide experimental efforts for searching for the formation of toroidal nuclei, we estimate the kinematics of the final fragments *prior* to the decay of the toroidal nuclei, at $t = 120$ fm/c, from our numerical BUU simulations,⁵ and the results are listed in Table 1. We further estimate various components of excitation energies using techniques outlined in Refs. 5, 8 and 10 and find that the toroidal nuclei formed are quite cold, with thermal excitation energies per nucleon, $\epsilon_{\text{thermal}}/A \approx 1-2$ MeV, at breakup ($t \approx 120$ fm/c). Thus the breakup process is a cold breakup process at low temperatures similar to the cold scission of an initially hot system well understood in fission processes. Because of the geometry of the toroids and because of cold breakup

$^{92}\text{Mo} + ^{92}\text{Mo}$, $E/A = 85$ MeV, $b=0$, Soft EOS

Figure 2 Same as Fig. 1, but calculated with the soft EOS.

at low temperatures, the decay fragments will have approximately similar masses, thus enhancing the cross sections for fragments with nearly-equal sizes at kinematic regions discussed below.

Guided by the BUU calculations, we predict a typical case of fragmentation into three ^{20}Ne -like fragments in a coplanar final state for $^{92}\text{Mo} + ^{92}\text{Mo}$ collisions at $E/A = 75$ MeV, each with kinetic energy per nucleon in the C.M. frame, $E_k/A \approx 1.8$ MeV, or total energy 36 MeV per ^{20}Ne fragment. These energies are very small and the fragments will therefore be focused to laboratory angles $\theta_{lab} \leq \theta_{max} \approx 16.7^\circ$. At higher energies, we predict typical cases of four ^{12}C -like and five ^7Li -like fragments, respectively at $E/A=85$ and 100 MeV. On the average, as the incident energy is increased, a larger number of IMF's with smaller mass per fragment is emitted to larger critical lab angles θ_{max} . We note here that the specific values of the multiplicities listed in Table 1 are used for the convenience of estimating the kinematics. In reality, large fluctuations in IMF multiplicities are expected, which is beyond what the BUU model can predict. However, although the kinetic energy may depend on the mass and

multiplicity, each fragment should have approximately the same C.M. kinetic energy *per nucleon*, thus these nearly-equal fragments are focused to angles less than $\theta_{lab} \lesssim 20^\circ$. We emphasize the specific kinematic regions because, in the systems considered, more than half of the mass and energy is emitted prior to the decay of the bubble and toroidal nuclei. These earlier emissions could make the experimental observations very complicated. Thus the best chance to see the enhancement of nearly-equal fragments is to focus the analysis to the specific kinematical regions where they are produced.

In summary, with our improved BUU model, we predict multifragmentation following the formation of metastable toroidal and bubble nuclei in $^{92}\text{Mo} + ^{92}\text{Mo}$ collisions. Based on our numerical simulations, we propose the following signatures for detecting the new phenomena: 1) because of the geometries of bubbles and toroids and because of the *cold* breakup at low temperatures, we predict enhanced cross sections for fragments with *nearly-equal* masses at *small* center-of-mass energies. Because of the small C.M. kinetic energies, these nearly-equal fragments are therefore focused to angles $\theta_{lab} \lesssim 20^\circ$ (Table 1); 2) the coplanarity of the emission pattern for the intermediate mass fragments with nearly-equal masses and C.M. energies at forward kinematics ($\theta_{lab} \lesssim 20^\circ$) may carry important information concerning the geometry of the sources. This, in turn, could provide information about the stiffness of the equation of state. Indeed, after we completed this work,⁵ we became aware of a paper by Bruno *et al.*¹¹ where they reported a significant enhancement for fragments with nearly-equal masses at kinematical regions similar to our predictions. This could be the first experimental evidence for the formation of bubble or toroidal geometry in heavy-ion collisions.

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TABLE 1
Multifragment decay from a metastable toroidal nucleus in $^{92}\text{Mo} + ^{92}\text{Mo}$ collisions predicted by our improved BUU model

E/A (MeV)	IMF	multi- plicity	E _x /A (MeV)	E _x (MeV)	θ_{max}
75	^{20}Ne	3	1.8	36	16.7°
85	^{12}C	4	2.4	29	19.1°
100	^7Li	5	2.9	20	20.9°

Polyhedron and Sausage Instabilities in the Decay of Bubble and Toroidal Nuclei

C. Y. Wong*, H. M. Xu, and B. Xiao

Recently, exotic nuclear shapes, analogous to those studied by C. Y. Wong,^{1,2} some time ago, were observed theoretically in BUU simulations.³⁻⁷ In the present work, we wish to examine symmetric configurations and instabilities leading to the breakup of toroidal and spherical bubble nuclei into equal fragments, with the liquid-drop model.⁸

We study first the breakup of a spherical bubble nucleus. The nuclear matter during the breakup stage has a surface tension whose coefficient σ depends on the temperature and the density. For breakup processes in intermediate-energy heavy-ion reactions, the nuclear shell effects can be neglected. The

deformation energy for the bubble nucleus, E_{def} can be expressed as

$$E_{\text{def}} = E_s^{(0)} [g_s(p) + 2xg_c(p)], \quad (1)$$

where $E_s^{(0)} = 4\pi\sigma R_0^2$ is the surface energy of an equivalent nucleus of radius R_0 which has the same volume, $x = (3Z^2e^2/5R_0) \div 2E_s^{(0)}$ is the fissility parameter, $p = R_1/R_2 \leq 1$ is the aspect ratio of the bubble nucleus with an inner radius R_1 and an outer radius R_2 (Fig. 1a). The geometrical factor $g_s(p)$ for the surface energy and $g_c(p)$ for the Coulomb energy are¹

$$g_s(p) = (1-p^3)^{-2/3}(1+p^2), \quad (2)$$

and

$$g_c(p) = (1-p^3)^{-5/3} \left(1 - \frac{5}{2}p^3 + \frac{3}{2}p^5 \right). \quad (3)$$

We consider the breakup of a spherical bubble nucleus into a regular n -polyhedron configuration with non-overlapping fragments of equal mass and charge (Fig. 1a). (We have checked that at the aspect ratios where the bubble or the toroidal nuclei can break up into many equal fragments, the fragments do not overlap.)

Figure 1. (a) Schematic picture of the decay of a bubble nucleus into a regular polyhedron configuration, and (b) the decay of a toroidal nucleus into a regular polygon configuration.

The deformation energy for the nuclear system in such a polyhedron configuration is

$$E_n = E_s^{(0)} \left[n^{1/3} + 2xn^{-2/3} + \frac{5x}{3n} \sum_{j=2}^n \frac{1}{(r_{1j}/R_0)} \right], \quad (4)$$

where r_{ij} , the distance between the i th and the j th fragments, can be evaluated from the geometry of regular polyhedrons.⁹ The distances from the fragments to the center of the polyhedron are taken to be the same as the mean distance of the nuclear matter of the bubble nucleus from its center. With

this identification, the energy E_n for the n -fragment configuration can be evaluated as a function of the aspect ratio p .

In Fig. 2 we show the deformation energy of a bubble nucleus E_{def} (solid curves) and the deformation energy E_n for an n -fragment regular polyhedron configuration (dashed curves), as a function of the aspect ratio $p = R_1/R_2$ for various values of the fissility parameter. As shown in Ref. [1], the deformation energy for a bubble nucleus will have a minimum in p if $x \geq 2.03$.

Figure 2. The deformation energy for the bubble configuration (solid curves) and the n -fragment regular polyhedron configuration (dashed curves) as a function of the aspect ratio, $p = R_1/R_2$, for a bubble nucleus with a fissility parameter $x=0.25$ (Fig. 2a), 0.5 (Fig. 2b) and 0.75 (Fig. 2c).

Here, we focus attention to the decay of bubble nuclei formed in heavy-ion collisions, with fissility parameters $x = 0.25, 0.50$, and 0.75 . For this range of fissility parameters, the deformation energy surface does not have a minimum. As the aspect ratio increases, the deformation energies of some low order polyhedron configurations are lower than that of the bubble configuration, and the breakup of the bubble nucleus into these polyhedron configurations is possible. Thus, a bubble configuration can break up into a regular polyhedron configuration with n vertices when $p \gtrsim 0.6 + 0.028(n-4) - 0.001(n-4)^2$. For a given multiplicity of fragments, the onset of the instability occurs at approximately the same aspect

ratio p , nearly independent of the fissility parameter.

We consider next the breakup of a toroidal nucleus. The deformation energy, E_{def} , of a toroidal nucleus can be written in the same form as Eq. (1) except that the aspect ratio $p=R/d$ is the ratio of the "major radius" R and the "minor radius" d (Fig. 1b).¹ The surface geometrical factor is $g_s(p) = (4\pi p/9)^{1/3}$. The Coulomb geometrical factor, $g_c(p)$, from Eq. (2.74) of Ref. [1], is

$$g_c(p) = \frac{5}{6} \left(\frac{3\pi}{2p^2} \right)^{1/3} \frac{(p^2-1)^{3/2}}{p} \left[\frac{8}{9\pi^3} \sum_{n=0}^{\infty} \epsilon_n B_n(p) C_n(p) - \frac{1}{8\pi} \frac{p}{(p^2-1)^{3/2}} (4p^2+3) \right], \quad (5)$$

where $\epsilon_n = 2/(1 + \delta_{n0})$, and B_n and C_n are

$$B_n(p) = \left(n + \frac{1}{2} \right) P_{n+1/2}(p) Q_{n-1/2}^2(p) - \left(n - \frac{3}{2} \right) P_{n-1/2}(p) Q_{n+1/2}^2(p), \quad (6)$$

$$C_n(p) = \left(n + \frac{1}{2} \right) Q_{n+1/2}(p) Q_{n-1/2}^2(p) - \left(n - \frac{3}{2} \right) Q_{n-1/2}(p) Q_{n+1/2}^2(p), \quad (7)$$

where P_m^n and Q_m^n are Legendre functions of the first and second kind with order n and degree m .¹

Our previous analysis¹ focused on the onset of sausage instability of a toroidal nucleus, which is found to be an important mode of decay. The sausage instability of order n leads to n identical fragments. We wish to concentrate here on symmetric shapes at a later stage, when separated fragments have been formed (Fig. 1b). The energy of the regular n -polygon configuration can be calculated with Eq. (4) except that the distance r_{ij} between fragment 1 and fragment j becomes

$$r_{ij} = 2R_f \sin \left[(j-1) \frac{\pi}{n} \right], \quad (8)$$

where R_f is the distance between a fragment and the center of the toroid and is taken to be the major radius R of the toroidal nucleus. With this identification, the deformation energy for an n -polygon configuration can be obtained as a function of the aspect ratio p .

Figure 3. The deformation energy for the toroidal configuration (solid curves) and the n -fragment regular polygon configuration (dashed curves) as a function of the aspect ratio, $p=R/d$, for a toroidal nucleus with a fissility parameters $x=0.25$ (Fig. 3a), 0.5 (Fig. 3b) and 0.75 (Fig. 3c).

In Fig. 3 we show the deformation energy of a toroidal nucleus E_{def} (solid curves) and the deformation energy E_n for an n -fragment regular polygon configuration (dash curves), as a function of the aspect ratio $p = R/d$ for various values of the fissility parameter. The deformation energy for a toroidal nucleus will have a minimum¹ in p if $x \geq 0.96$. In the range of fissility parameters shown in Fig. 3 ($x = 0.25, 0.50$, and 0.75), the deformation energy surface does not have a minimum. It rises as the aspect ratio p increases. As the aspect ratio increases, the deformation energy for the toroidal configuration becomes greater than the deformation energies of some of the polygon configurations, and the decay of a toroidal nucleus into these configurations is possible. The onset of the

instability for an n -fragment configuration depends on the aspect ratio, but is otherwise rather insensitive to the fissility parameter. As the aspect ratio becomes greater, the channel for the decay into a greater number of fragments begins to open up. As one can see from Fig. 3, the decay mode for n fragments opens up at the aspect ratio $p \approx 0.7n$, which is close to the location for the onset of instability given just by the surface energy alone. This indicates that for toroidal nuclei, the drive towards instability due to the variation of the Coulomb energy is small compared to that due to the variation of the surface energy, particularly for systems with a small fissility parameter.

In summary, with a liquid-drop model, we examine the relationship between the geometry of the bubble or the toroidal nucleus and the number of fragments into which they can break up. We demonstrate that the decay channel for a greater multiplicity opens up at a larger ratio of the inner to the outer radius of the bubble nucleus, or a larger ratio of the major to the minor radius of the toroidal nucleus.

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Disappearance of Flow and the In-Medium Nucleon-Nucleon Cross Section

H. M. Xu

One of the most challenging questions in nucleus-nucleus collisions is extracting information about the nuclear equation of state (EOS) and the in-medium nucleon-nucleon cross section. In a earlier flow study for $^{40}\text{Ar} + ^{27}\text{Al}$ collisions,¹ we demonstrated that the upper limits of E_{bal} (determined by the re-appearance of flow) were sensitive to the lower limits of the in-medium nucleon-nucleon cross section. Because the upper limit of E_{bal} was not available for $^{40}\text{Ar} + ^{27}\text{Al}$ system, only the upper limit of the in-medium nucleon-nucleon cross section was reliably obtained.¹

To investigate whether one can obtain quantitative information concerning the in-medium nucleon-nucleon cross section from recent MSU data, we have performed improved BUU calculations² for $^{40}\text{Ar} + ^{51}\text{V}$ collisions. Experimental study of this system clearly showed the re-appearance of flow at higher energies.³ In Figure 1, we show the flow parameter as a function of incident energy for calculations at $b=2$ (top panel) and 4 fm (bottom panel), respectively. The solid-circles, triangles, diamonds and the open-triangles indicate calculations for the stiff EOS and $\sigma_{NN} = 41, 35, 30, 25$ mb,

respectively. The open-circles indicate calculations for the soft EOS and $\sigma_{NN} = 41$ mb. Clearly, the calculations indicate similar values of E_{bal} for both the stiff and the soft EOS, when σ_{NN} is fixed at 41 mb. This insensitivity to EOS is significant because it eliminates the dual sensitivities (to both EOS and σ_{NN}) shown in other observables which often make the extraction of EOS or σ_{NN} difficult. Indeed, significant sensitivities of the flow to σ_{NN} are observed, with smaller values of σ_{NN} yield higher values of E_{bal} , consistent with earlier calculations.¹

Figure 1. The flow parameter as a function of incident energy for $^{40}\text{Ar} + ^{51}\text{V}$ collisions at $b=2$ (top panel), and 4 fm (bottom panel), respectively. The solid-circles, triangles, diamonds and open triangles display the BUU calculations with a stiff equation of state and $\sigma_{NN} = 41, 35, 30$, and 25 mb, respectively. The open circles are calculations with a soft equation of state and $\sigma_{NN} = 41$ mb. The solid squares with horizontal error bars indicate experimental data taken from Ref. 3. The lines are used to guide the eyes.

The solid squares with horizontal error bars are experimental values of E_{bal} , taken from Ref. 3, where a simultaneous χ^2 fit to spectra of protons, deuterons, tritons and $Z=2$ light particles was used to obtain the value of E_{bal} . The uncertainty in the experimental data was limited mainly by the fact that only one higher energy point, at $E/A = 100$ MeV, was measured which clearly showed the re-appearance of flow. This error bars could be further reduced when more experimental data at higher incident energies are available. Compared with the present data, the calculations clearly exclude values of σ_{NN} significantly below $\sigma_{NN} \approx 30$ mb or above $\sigma_{NN} \approx 40$ mb. Moreover, the calculations indicate that there is still room to reduce further the range of σ_{NN} when more accurate value of E_{bal} is available.

In conclusion, we have investigated the disappearance of flow for central $^{40}\text{Ar} + ^{51}\text{V}$ collisions with improved BUU calculations. We demonstrated, for the first time, that the in-medium nucleon-nucleon cross section can be narrowed down to $\sigma_{NN} \approx 30-40$ mb by comparing the calculations with the experimental data.

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Mass Asymmetry, Equation of State, and Nuclear Multifragmentation

Hong Ming Xu

Experimental investigations on the decay of hot nuclei have reported striking observations. For Ar induced reactions, cross sections for evaporation and fission residues appear to vanish at energies in excess of $E/A \approx 35\text{--}40$ MeV.^{1,2} In contrast, for carbon induced reactions, fission has been observed up to energies as high as $E/A = 84$ MeV.³ More recently, multifragment emission is observed for Ar, Ca and Xe⁴⁻⁷ induced reactions and the average number of intermediate-mass fragments is larger for Xe than that for Ar or Ca induced reactions.

Figure 1 BUU calculations with the soft EOS for $^{92}\text{Mo} + ^{92}\text{Mo}$ collisions at $E/A = 75$ MeV, $b=0$. From top to bottom are at time steps of 0, 60, 120, 240 fm/c, respectively.

To study the mass dependence of multifragment disintegration and the dependence on equation of state

Figure 2 The top view of BUU calculations for $^{40}\text{Ar} + ^{51}\text{V}$ (left panels) and $^{12}\text{C} + ^{51}\text{V}$ (right panels) collisions. Details are discussed in the text.

(EOS), we have performed improved Boltzmann-Uehling-Uhlenbeck (BUU) calculations.⁸ Typical examples of our calculations are shown in Figs. 1-2 for $^{92}\text{Mo} + ^{92}\text{Mo}$, $^{12}\text{C} + ^{51}\text{V}$ and $^{40}\text{Ar} + ^{51}\text{V}$ collisions. For $^{92}\text{Mo} + ^{92}\text{Mo}$ collisions at $E/A = 75$ MeV, $b=0$ (Fig. 1), and calculated with the soft EOS, a compressed state is formed at $t \approx 30$ fm/c. This compressed state expands nearly

isotropically and develops quickly into what appears to be a genuine multifragmentation, with fragments of similar sizes distributed on the surface of an expanding hollow sphere. To see the dependence on the equation of state, we show in Fig. 2 the top view of $^{40}\text{Ar} + ^{51}\text{V}$ collisions (left hand panels) at $E/A = 75$ MeV, $b=0$, $t = 240$ fm/c, for both the soft EOS (central two panels, with different initializations) and the stiff EOS (bottom panel). For the soft EOS at this energy one always observes 3 or 4 fragments. For the stiff EOS, however, one sees a well defined single residue in the final state. The right hand panels of Fig. 2 show the top view of head-on collisions for a even lighter system, $^{12}\text{C} + ^{51}\text{V}$, calculated with the soft EOS, but at higher energies, $E/A = 75$ (second panel from top), 150 (third), and 200 (bottom) MeV. For this system, one always sees a well defined residue up to the highest energy calculated.

To see this more clearly, we show in Fig. 3 the evolution of the average density, defined as $\langle \rho \rangle = \int_D \rho^2 d^3r / (\int_D \rho d^3r)$,⁹ as a function of time. Here D indicates regions of $\rho \geq 7\% \rho_0$. The top panel shows the comparisons at a given incident energy, $E/A = 75$ MeV. For $^{12}\text{C} + ^{51}\text{V}$ collisions (dotted lines), the system exhibits a behavior similar to a damped monopole oscillation,¹⁰ with negligible maximum compression, $\langle \rho \rangle_{\max} \leq 1.1\langle \rho_0 \rangle$, at $t \approx 25$ fm/c and modest maximum expansion, $\langle \rho \rangle_{\min} \approx 0.5\langle \rho_0 \rangle$, at $t \approx 60$ fm/c. In contrast, for $^{40}\text{Ar} + ^{51}\text{V}$ collisions calculated with the soft EOS (dashed lines), where multifragmentation is observed, the system is first compressed to $\langle \rho \rangle_{\max} \approx 1.25\langle \rho_0 \rangle$ at $t \approx 25$ fm/c. It then expands substantially to very low densities, $\langle \rho \rangle_{\min} \leq 0.15\langle \rho_0 \rangle$, at $t \approx 100$ fm/c. Afterwards, the density increases gradually, reflecting the condensation from a dilute system into several individual fragments. Hence the onset of multifragmentation could be viewed as a result of the gradual disappearance of damped oscillations when compression and expansion are increased. Indeed, if the system is stressed to beyond its limits to restore to a single system, it will break up into several fragments. This is clearly illustrated in the central

Figure 3 The average density as a function of time. For each set of parameters, four trajectories corresponding to different initializations are displayed. For details, see text.

panel of Fig. 3, where we display calculations for the same system, $^{40}\text{Ar} + ^{51}\text{V}$, but at different energies, $E/A = 35$ (dotted lines), 55 (solid lines), and 75 (dashed lines) MeV, respectively. As the energy is increased, compression, and particularly, expansion become larger. As a result, the oscillation mechanism shown at low energies disappears when the system expands to $\langle \rho \rangle_{\min} \leq 0.15\langle \rho_0 \rangle$ at energies $E/A = 75$ MeV. This result is further supported by calculations for $^{12}\text{C} + ^{51}\text{V}$ collisions shown in the

bottom panel of Fig. 3, where oscillations persist up to energy $E/A \approx 200$ MeV for which no fragmentation is observed.

To investigate whether there is a critical compression or expansion for which multifragmentation channel opens up, we show in the top panel of Fig. 3 calculations for $^{40}\text{Ar} + ^{51}\text{V}$ collisions with the stiff EOS (solid lines), where single residues are formed at $E/A = 75$ MeV. Although the final states are completely different (see Fig. 2), similar maximum densities are reached for both the stiff and the soft EOS. The difference, however, becomes noticeable during the later expansion stages which lead to completely different final configurations. Thus it is mainly the property of EOS at the later expansion stages that determines the final multifragmentation. Stiffer EOS has a larger surface tension and therefore its tendency for a system to break up becomes less. Although it appears too early to determine a critical compression, it may nevertheless be possible to determine a critical maximum expansion since the major dynamical process is already over when the system reaches the maximum expansion. For $^{40}\text{Ar} + ^{51}\text{V}$ collisions, we find that the critical minimum density for the system to break up appears to be very low, $\rho \approx 0.15\rho_0$.

To assess the role of thermal excitation, we have decomposed the *transverse* excitation energy approximately into three components, energy associated with compression or expansion, E_{exp}^* , collective energy, E_{coll}^* , and thermal energy, E_{the}^* , respectively,⁸ using a technique similar to that outlined in Ref. 10, but considering only the transverse components. In this decomposition, E_{exp}^* represents the energy change when the density distribution of the system is changed away from that of a ground state nucleus (e.g., the creation of surfaces due to fragmentation). As shown in Fig. 4, both the collective energies, E_{coll}^*/A_{res} (central panel), and the thermal energies, E_{the}^*/A_{res} (bottom panel), reach maximum values at $t \approx 40$ -50 fm/c. As a result, the systems expand and the energies stored in density, E_{exp}^*/A_{res} (top panel), reach maximum values at slightly later times. Clearly, the

Figure 4. The decomposition of transverse excitation energy into energies associated with expansion, collective and thermal energies for $^{40}\text{Ar} + ^{51}\text{V}$ and $^{12}\text{C} + ^{51}\text{V}$ collisions. For details see text.

maximum energies per nucleon associated with collective expansion, both E_{exp}^*/A_{res} and E_{coll}^*/A_{res} , are much larger for $^{40}\text{Ar} + ^{51}\text{V}$ system than that for $^{12}\text{C} + ^{51}\text{V}$ system, independent of equations of state. In contrast, similar maximum thermal excitation energies per nucleon are reached for both ^{12}C and ^{40}Ar induced reactions at $t \approx 40$ -50 fm/c. This suggests that the dynamical and collective expansion, rather than the thermal excitation, plays

the dominant role for multifragmentation processes.

In conclusion, with an improved BUU model, we have studied effects of mass asymmetry and effects of the equation of state in nuclear multifragmentation processes. We demonstrate that, the dynamics of compression and expansion, rather than the thermal excitation energy, plays the dominant role in causing the observed multifragmentation.

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Symmetric Multi-Fragmentation Barriers and Their Temperature-Dependence

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Many experimental results indicate that after a violent collision, nuclear disassembly occurs.¹ Whether or not complete equilibration is achieved during the collision, the prompt fragments may need to overcome a barrier. Development of the barrier for multi-fission/fragmentation can be expected to be faster than the fragment emergence time, because the collective motion is slow. Barriers were calculated for ternary fission²⁻⁴ and for multi-fold fission up to 8 fold recently by F. Haddad and G. Royer.⁵

We suggest a general description of the multi-fragmentation shape as follows. Shapes consisting of a series of pear-like bodies surrounding a inner joined sphere are assumed to be those associated with symmetric fission or fragmentation into two or more fragments. The surface of the pear-like body satisfies the following expression:

$$\rho^2 = \delta \cos a_m \theta + \sqrt{1 - \delta^2 \sin^2 a_m \theta} \quad (1)$$

where the multiplier a_m of the angle θ is 2, 3, 3.29,

6 fold fission shape, $\delta=0.0$ to 1.0, step 0.1

Figure 1. The shape for 6 fold fission from $\delta = 0.0$ (solid line) to 1.0 (dotted line), a sphere deforms smoothly to scission; the two fragments below and above the $z=0$ plane are not shown.

4 and 5.1 for binary, ternary, 4, 6 and 8 fold respectively. In expression (1) the fold is noted by subscript m and δ is a unique deformation parameter, it changes from 0 (spherical) to 1 (at scission). With

increasing δ the inner joined sphere with radius of $\sqrt{1-\delta}$ becomes smaller and vanishes at scission. The shape in the binary case, the so-called Cassinian ovaloid shape,⁶ has been shown to be a good approximation.^{7,8}

Figure 2. The shape of one fragment branch for 3-, 4-, 6- and 8-fold fission (a), (b), (c) and (d), respectively.

In Fig. 1 the 6 fold fission deformation as a function of δ is shown in the $z=0$ plane, and also one branch of the deformation shapes for 3, 4, 6 and 8 fold fission is also shown, respectively in Fig.2(a)-(d).

Figure 3. The Volume conservation factor $f_v(\delta, m)$ and relative Surface energy $B_s(\delta, m)$ for $m=4, 6$ and 8 .

The spatial distributions of fission fragment at

scission are triangular for 3-fold fission, tetrahedral for 4-fold fission, octahedral for 6-fold fission and cubic for 8-fold fission. The angles between adjacent symmetric axes of branches associated with (1) are 120° , 109.47° , 90° and 70.53° corresponding to 3, 4, 6 and 8 fold, respectively.

4,6&8 fold symmetric fission, E_c/E_{c0} vs δ

Figure 4. The relative Coulomb energy B_c as a function of δ for 4-, 6-, 8- and 8c-fold fission.

With the shape of expression (1), the volume conservation factor, $f_v(\delta, m)$ and relative surface energy $B_s(\delta, m) = E_s/E_{s0}$ and related Coulomb energy $B_c(\delta, m) = E_c/E_{c0}$ for $m=4, 6$ and 8 were calculated and are shown in Figs. 3 and 4, respectively. In Fig. 4, the difference between the 8 fold and 8c-fold is that the 8-fold case is cubic; while for the 8c case the position of 4 fragments in one plane is rotated 45° about the center axis of the cube; i.e, the positions are staggered rather than eclipsed when viewed at the appropriate face.

Using this parameterization method, the fission barriers have been calculated for 2, 3, 4, 6 and 8 fold multi-fragment final states. As an example, in Fig. 5 the fission barriers for ^{252}Cf are shown. Here the Proximity effects⁹ between adjacent branch surfaces are included. For the total kinetic energy (TKE) or the so-called Coulomb energy, the calculated values in units of E_{c0} and $(Z^2/A^{1/3})$ are listed in Table I. The values TKE' are estimated by putting m equal point charges at the Z_{cs} positions; here Z_{cs} is center of mass for one fragment as calculated from the

Multi-symmetric fission barrier for ^{252}Cf

Figure 5. The fission potential as a function of fragment elongation in ^{252}Cf for various folds. The different lines correspond to different folds as indicated.

shape equation (1). The actual TKE values are a little bit larger than TKE' , because the charge distribution of a fragment is not completely symmetric about the point, Z_{cs} . For binary fission, the TKE value is in good agreement with experimental data. As mentioned above, the calculated multi-fold barriers may also be important multi-fragmentation processes.

For very heavy isotopes with fissility x larger than 1, no barrier is expected for binary fission however there are still barriers for multi-fission. For example, the ternary barrier is 7-8 MeV in the $Z=134$ and $A=352$ system; and the 4-fold barrier decreases from 50 MeV at zero temperature to 20 MeV at a temperature of 5 MeV.

The temperature dependence¹⁰ of these fission barriers is calculated as shown in Fig. 6. In addition to the barrier heights B_f for ^{208}Pb , plotted in Fig. 7, the locus of the de-exciting system in E_x, T space (assuming $E_x = aT^2/10$) is also presented. This latter may be compared with the calculated barriers. At high excitation energy, the nucleus de-excites rapidly by particle emission. Times for the fission processes are relatively slow, of the order of 10^{-20} seconds.¹¹⁻¹³ The hatched region in the figure indicates schematically an excitation energy region

Figure 6. The Dependence of fission barrier on nuclear temperature for binary (a), ternary (b), 4-fold (c), 6-fold (d) and 8-fold (e) events, respectively. The symbols correspond to different nuclei as indicated.

where the cumulative decay times from initial excitation energies in the ranges of 3-6 AMeV become comparable to such fission times. This picture suggests that the dynamic delays may inhibit the higher fold fission decay since the times required for these processes may be longer than the times for the nucleus to de-excite to energies which are well below the barriers for these higher fold decays. Determinations of the probabilities and delay times for higher fold fission processes might provide useful information on both the nuclear viscosity and the temperature dependence of the surface energy.^{14,15}

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Symmetric Multi-fission barrier vs nuclear temperature for ^{208}Pb

Figure 7. Schematic representation of the relationship between the barriers calculated for ^{208}Pb and the excitation energy at which fission is expected to compete statistically. (see text)

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Table I.
Total Kinetic Energy (TKE) in Multi-fragmentation

Folds, m	2	3	4	6	8	8c
TKE/E_{co}	0.178	0.234	0.2869	0.3435	0.3528	0.3520
$TKE/(Z^2/A^{1/3})$	0.126	0.165	0.202	0.242	0.249	0.248
TKE'/E_{co}	0.178	0.225	0.2769	0.3337	0.3451	0.3441

Subthreshold Kaon Production in Nucleus-Nucleus Collisions

X. S. Fang, C. M. Ko, and Y. M. Zheng*

Experiments on kaon production from heavy-ion collisions are being carried out at the Superconducting Synchrotron Accelerator (SIS) in GSI.¹ The incident energy per nucleon at the collision is around 1 GeV and is below the threshold energy of 1.56 GeV for kaon production in the nucleon-nucleon collision in free space. One of the motivations for this study is to learn about the nuclear equation-of-state at high densities. As first pointed out in Ref. 2, the kaon yield from heavy-ion collisions at subthreshold energies can differ by a factor of three depending on the stiffness of the nuclear equation-of-state at high densities. Similar effects have been obtained recently using the covariant BUU model³ and the covariant quantum molecular dynamics.⁴

In the transport model for heavy-ion collisions, kaons are usually treated as free particles. We have, however, generalized the relativistic transport model⁵ to include both the kaon mean-field potential and the collisions of kaons with other particles.

The relativistic transport model is based on the transport equation for the phase space distribution function $f(x, \mathbf{p}^*)$ of nucleons of an effective mass $m^* = m - g_\sigma \langle \sigma \rangle$ and momentum $\mathbf{p}^* = \mathbf{p} - g_\omega \langle \omega \rangle$. In the above, g_σ and g_ω are the coupling constants of a nucleon to the scalar (σ) and vector (ω) mesons, respectively. The expectation values of the scalar meson $\langle \sigma \rangle$ and the vector meson $\langle \omega \rangle$ are related in the mean-field approximation to the nuclear scalar and current densities. The relativistic transport model is solved using the method of pseudoparticles in which each nucleon is replaced by a collection of test particles. The propagation of these test particles is then described by the classical equations of motion.

The coupling constants are determined from the nuclear matter property. Choosing the nucleon effective mass $m^* = 0.83m$ at the normal nuclear density and allowing the scalar meson self-interactions, we have obtained in Ref. 5 two

parameter sets. They correspond to a soft and a stiff nuclear equation-of-state with a compressibility of 200 MeV and 380 MeV, respectively.

The delta particle is also included and its propagation is treated similarly to the nucleon. Collisions among nucleons and deltas are treated as in the cascade model. Besides elastic scattering, both nucleons and deltas can interact inelastically via $NN \leftrightarrow N\Delta$. The pion degree of freedom is also included via $\Delta \leftrightarrow \pi N$, and it is, however, assumed to propagate as a free particle in the nuclear medium.

To include kaons in the transport model, we first note that because of the explicit chiral symmetry breaking, nucleons act on kaons as an effective scalar field.^{6,7} This leads to an attractive s -wave interaction for the kaon. There is also a vector interaction in the chiral Lagrangian, which leads to an s -wave repulsive vector potential for a kaon in the nuclear matter.⁸ As a result, the kaon effective mass is modified in the medium, i.e.,

$$m_K^{*2} \approx m_K^2 \left[1 - (\Sigma_{KN}/m_K - 3/4)(\rho_B/f_K^2 m_K) \right],$$

where ρ_B is the baryon density, the kaon decay constant is $f_K \sim 93$ MeV and the KN sigma term has value $300 \text{ MeV} \leq \Sigma_{KN} \leq 600 \text{ MeV}$.

The propagation of kaons with the in-medium mass is then treated similarly as nucleons. Representing the kaon by test particles, its motion is again given by the classical equations of motion.

The kaon-nucleon collision is included by using a kaon-nucleon total cross section⁹ of about 10 mb which we take to be density-independent. After the collision the kaon direction is isotropically distributed as the kaon-nucleon interaction is mainly in the s -wave. Since kaon production is treated perturbatively, its effect on nucleon dynamics is neglected. We therefore do not allow the nucleon momentum to change in a kaon-nucleon interaction.

Figure 1. One-pion exchange model for $NN \rightarrow \Lambda K$.

The dominant process for kaon production in heavy-ion collisions at subthreshold energies is from the nucleon-nucleon interaction.¹⁰ It can be approximately described by the one-pion-exchange model. The corresponding Feynman diagram is shown in Fig. 1. The isospin-averaged cross section can be written in terms of the isospin-averaged cross section for the virtual process $\pi N_2 \rightarrow \Lambda K$ which we approximate by the on-shell cross section and is modeled through intermediate states such as $N_1^*(1650)$, $N_2^*(1710)$, and $N_3^*(1720)$ as they have appreciable probability of decaying into ΛK .

Figure 2. Energy dependence of the cross section $NN \rightarrow \Lambda K$ at densities of $0\rho_0$ (dashed), $1\rho_0$ (thick solid), $2\rho_0$ (dashed-dotted), $3\rho_0$ (dotted), and $4\rho_0$ (thin solid).

The calculated kaon production cross section from $NN \rightarrow \Lambda K$ in free space is shown by the

dashed curve in Fig. 2 as a function of the center-of-mass energy. For the energy range we are interested in, the one-pion-exchange model gives a reasonable description of the data.¹¹

Kaons can also be produced from nucleon-delta and delta-delta interactions. The corresponding cross sections have been estimated in Ref. 12 and it was found that $\bar{\sigma}_{N\Delta \rightarrow N\Lambda K} \approx 3/4 \bar{\sigma}_{NN \rightarrow N\Lambda K}$ and $\bar{\sigma}_{\Delta\Delta \rightarrow N\Lambda K} \approx 1/2 \bar{\sigma}_{NN \rightarrow N\Lambda K}$ at the same center-of-mass energy.

To determine the kaon production cross section in the medium, we simply use the in-medium masses in the one-pion exchange model. For the in-medium nucleon and kaon masses, we use those introduced above. The pion mass is assumed to be unchanged in the matter. The lambda mass in the medium is given by $m_\Lambda^* = m_\Lambda - g_{\sigma\Lambda\Lambda} \langle \sigma \rangle$, where the lambda-scalar meson coupling constant $g_{\sigma\Lambda\Lambda}$ is about two-thirds of the nucleon-scalar meson coupling constant g_σ .¹³ For N^* resonances we take $m_{N^*}^* = m_{N^*} - g_\sigma \langle \sigma \rangle$ with the same coupling constant to the scalar meson as the nucleon. Their widths are then calculated with the density-dependent masses. The branching ratio of their decay into πN and ΛK are, however, assumed to be unchanged in the medium.

The kaon production cross section in the medium is shown in Fig. 2 for different densities. It is seen that the threshold for kaon production is reduced significantly in the nuclear medium. The magnitude of the kaon production cross section decreases, however, slightly with the density.

Because of the small probability for kaon production in baryon-baryon interactions, kaon production in heavy-ion collisions at subthreshold energies can be treated perturbatively so that the collision dynamics are not affected by the presence of produced kaons. When the energy in a baryon-baryon collision is above the threshold for kaon production, the kaon is produced isotropically in the baryon-baryon center-of-mass frame with a momentum distribution taken to be the same as in free space.¹² The invariant double differential cross section for kaon production in heavy-ion collisions is then obtained by summing over the impact parameter.

To obtain the final kaon spectrum, we weight each kaon with the production probability introduced previously.

Figure 3. Kaon kinetic energy spectra at different laboratory angles for Au+Au collisions at 1 GeV/nucleon. The experimental data at 44° are also shown.

We have carried out a calculation for the collision of two Au nuclei at an incident energy of 1 GeV/nucleon using the relativistic transport model that includes all the medium effects, i.e., the in-medium kaon mass, density-dependent production cross section, and the final-state interactions of the kaon. With the soft equation-of-state (200 MeV), the kaon kinetic energy spectra at different laboratory angles are shown in Fig. 3. The theoretical results at 45° are seen to agree in both magnitude and the spectrum shape with the data at 44° from SIS,¹ shown by the open squares. All kaons are produced from the compression stage of the collision when the nuclear density is high. As in previous studies,^{2,11} the delta-nucleon interaction accounts for more than 60% of the produced kaons.

If a stiff equation-of-state (380 MeV) is used in the calculation, the kaon yield is reduced by a factor of ~ 3 . Using the free kaon production cross section leads to a factor of ~ 3 reduction in the kaon yield. Neglecting the final-state interactions of kaons reduces the kaon yield and the slope of its spectra at large angles as in Ref. 14,15. On the average, a

kaon undergoes about 4 rescatterings as it is produced mainly in the high density region.

In summary, we have generalized the relativistic transport model to include the kaon mean-field potential and the collisions of kaons with other particles. Our preliminary results on the kaon kinetic energy spectra for the collision between two Au+Au nuclei agree with the preliminary data from SIS at GSI if we use a soft equation-of-state with a compressibility of 200 MeV. With the stiff equation-of-state (380 MeV), the kaon yield is about a factor of 3 smaller than the data. Due to the lack of data on kaon production from the nucleon-nucleon interaction near the threshold and the complexity of the collision dynamics, our conclusion that the nuclear equation-of-state is soft is thus tentative but is very encouraging. With more refined study in the future, we shall be able to learn more about both the nuclear equation-of-state at high densities and the property of kaon in dense matter.

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Medium Effects on the Rho Meson

M. Asakawa and C. M. Ko

We have recently studied the ρ meson property in nuclear medium in the vector dominance model (VDM).^{1,2} Including the coupling of a ρ meson to pions, which are further modified by the delta-hole polarization of the medium, we find that with increasing nuclear density the position of the ρ meson peak in the spectral function moves to larger invariant masses and at the same time its width increases.³ Similar conclusions have also been obtained by Hermann *et al.*⁴ We have further found that the in-medium ρ meson mass is, however, reduced if the bare ρ meson mass in the model is assumed to decrease in the medium according to the scaling Ansatz of Brown and Rho.⁵ We have thus concluded that the mean-field effect, parameterized by the scaling mass in Ref. 3, is more important than the loop corrections calculated by the VDM.

A more consistent way of incorporating the mean-field effect is through the QCD sum rules.⁶ In terms of quarks, the current for a ρ meson is given by $J_\mu = (\bar{u}\gamma_\mu u - \bar{d}\gamma_\mu d)/2$. Its correlation function in the medium $\Pi_{\mu\nu}(q) = i \int e^{iqx} \langle T J_\mu(x) J_\nu(0) \rangle_\rho d^4x$, where $\langle \dots \rangle_\rho$ denotes the expectation value in the medium, can be expressed in terms of the transverse and longitudinal parts. At zero momentum, $q = 0$, the two are, however, related and only the longitudinal correlation function Π is needed.

The real and imaginary parts of the correlation function are related by the dispersion relation. For

large Euclidean four momenta, $Q^2 (= -q^2 = -s) \rightarrow \infty$, the real part can be evaluated perturbatively by the operator product expansion.⁷ The imaginary part of the correlation function at $s > 0$ is parameterized phenomenologically by a contribution from the ρ meson and a continuum. In normal QCD sum rules,⁸ the ρ meson spectral function is taken to be a delta function, i.e., $\delta(s - m_\rho^2)$. Here we shall use the one from the vector dominance model that includes the effect from the delta-hole polarization, i.e.,

$$S(s) = -2\Sigma_I / [(s - m_\rho^2 - \Sigma_R)^2 + (\Sigma_I)^2],$$

where Σ_R and Σ_I are, respectively, the renormalized real and imaginary parts of the ρ meson self-energy as calculated in Ref. 3. The bare ρ meson mass m_ρ is about 770 MeV in free space but becomes density-dependent in the medium due to the change of the quark condensate.

To suppress the contribution from higher order operators and to remove the need for subtractions in the dispersion relation, one usually introduces the Borel transform. Carrying out the Borel transform of both sides of the dispersion relation and taking the ratio of the resulting equation to its derivative with respect to $-1/M^2$, we obtain

$$\left[\int_0^{s_0} e^{-s/M^2} S(s) ds \right] / \left[\int_0^{s_0} e^{-s/M^2} S(s) / s ds \right] = N/D,$$

where s_0 is the threshold for the continuum while N and D are expressed in terms of quark and gluon condensates in the medium.

To determine the ρ meson mass m_ρ^* in the nuclear medium, we solve the sum rule in two steps. We first minimize N/D on the right hand side of the sum rule with respect to the Borel mass M for an optimal threshold s_0 . Then the bare ρ meson mass m_ρ in the spectral function $S(s)$ is determined by equating the left hand side of the sum rule, to the determined N/D . In the range of Borel masses $0.55 \leq M^2 \leq 0.75 \text{ GeV}^2$, this procedure is found to work very well.

We find that the bare ρ meson mass m_ρ decreases with increasing nuclear density as a result of the reduced quark condensate in the medium. The in-medium ρ meson mass m_ρ^* , determined by the pole of the ρ meson propagator, i.e., $F(m_\rho^*) = m_\rho^{*2} - m_\rho^2 - \Sigma_R = 0$, is shown by the solid curve in Fig. 1. It is about 530 MeV and 220 MeV at normal and twice normal nuclear matter density, respectively. The corresponding continuum threshold s_0 is about 0.87 GeV^2 and 0.47 GeV^2 , respectively. We have also shown in this figure by the dotted curve the in-medium ρ meson mass determined from the usual QCD sum rules using a delta function for the ρ meson spectral function.⁸ We see that our values are similar to those from the normal QCD sum rules calculation.

Figure 1. The density dependence of the ρ meson mass. The solid curve is obtained with the ρ meson spectral function evaluated in the vector dominance model that includes the Δ -hole polarization of the nuclear medium. The dotted curve is from the usual QCD sum rules calculation assuming that the ρ meson spectral function is a δ function.

The ρ meson spectral function in the medium, is shown in Fig. 2. We see that as the peak of the spectral function moves to smaller invariant masses, $M = s^{1/2}$, its width also becomes smaller. These results are qualitatively similar to those of Ref. 3 using the scaling ρ meson mass in the vector dominance model.

In conclusion, we have introduced a consistent method to incorporate the effects of both mean-field and loop corrections in the ρ meson property in dense nuclear matter. This is achieved by using the spectral function calculated from the vector dominance model in the hadronic side of the QCD sum rules. The in-medium ρ meson mass is found to decrease in matter. This confirms our previous results based on the scaling mass that the mean-field effect is more important than the loop corrections.

Figure 2. The spectral function of a ρ meson. The solid curve is for a ρ meson in free space. For a ρ meson in the medium, the dotted and dashed curves correspond, respectively, to nuclear densities of ρ_0 and $2\rho_0$, where ρ_0 is the normal nuclear matter density.

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Seeing the QCD Phase Transition with Phi Mesons

M. Asakawa and C. M. Ko

Heavy-ion experiments offer the possibility to create in the laboratory the deconfined quark-gluon plasma. Many experimental observables have been proposed as possible signatures for its existence.¹ We have shown previously that M_T scaling in the dilepton spectrum between the ϕ and J/ψ peak is a plausible signature for the quark-gluon plasma expected to be formed in future experiments at the Relativistic Heavy Ion Collider (RHIC) and the Large Hadron Collider (LHC).²

As the phi meson mass in hot hadronic matter is expected to decrease due to partial restoration of the chiral symmetry, a low mass phi peak besides the normal one will appear in the dilepton spectrum if the quark-gluon plasma is formed in the collision. This double phi peak structure can thus be used as a signature for identifying the phase transition of the quark-gluon plasma to hadronic matter in ultrarelativistic heavy ion collisions.

Figure 1. The temperature-dependent phi meson mass in the hot hadronic matter.

This scenario can be described more quantitatively. The phi meson mass at finite temperatures can be determined using the QCD sum rules,³ which relate via the dispersion relation the phi meson mass to the quark and gluon condensates in matter. For example, the strange quark condensate at finite temperatures $\langle \bar{s}s \rangle_T$ is approximately related to its value at zero temperature $\langle \bar{s}s \rangle_0$, $\langle \bar{s}s \rangle_T \approx \langle \bar{s}s \rangle_0 + \Sigma_h \langle \bar{s}s \rangle_h \rho_h$, where $\langle \bar{s}s \rangle_h$ and ρ_h are, respectively, the strangeness content and density of hadron h . Assuming that all hadron densities are given by the equilibrium ones, the resulting temperature dependence of the strangeness condensate can be calculated. We show in Fig. 1 the temperature dependence of the mass of a phi meson at rest m_ϕ in the hot hadronic matter with zero baryon density.⁴ We see that the phi meson mass decreases at high temperatures.

The QCD sum rules have also been used to study the masses of other vector mesons in the hot hadronic matter.⁵ It has been found that the temperature dependence of the rho meson mass is approximately given by

$$m_\rho(T)/m_\rho(T=0) \approx [1 - (T/T_c)^2]^{1/6},$$

where T_c is the critical temperature for the chiral restoration transition. However, the omega meson mass does not change much with temperature as it has a different isospin structure from that of the rho meson.⁵

Using the hydrodynamical code of Ref. 6, we have carried out a boost-invariant hydrodynamical

the low mass peak and increases with the initial temperature as a result of the appreciable transverse flow at freezeout.

In conclusion, we have shown that the recent predictions from the QCD sum rules on the change of vector meson masses in hot hadronic matter have dramatic effects on the dilepton invariant mass spectrum from ultrarelativistic heavy ion collisions. Due to the dropping phi meson mass in hot matter, a low mass peak besides the normal one appears in the dilepton spectrum if the quark-gluon plasma is formed in the collision. This low mass phi meson peak is thus a viable signal for the phase transition from the quark-gluon plasma to the hadronic matter. Furthermore, it also allows us to determine the transition temperature between these two phases of matter.

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**ATOMIC MOLECULAR AND
MATERIALS SCIENCE**

High Resolution Study of X-ray Emission Induced by 6- and 8-AMeV Xe Ions Incident on Solid Targets

V. Horvat, R. Parameswaran, and R. L. Watson

A study of x-ray emission induced by collisions of 6- and 8-AMeV Xe ions in solid targets has been initiated for the purposes of (a) extending previous work on single-K plus multiple L-shell ionization of target atoms to higher Z projectiles, and (b) examining the characteristics of L x-ray emission from high-Z, highly-charged ions.

In pursuit of the first objective, a curved crystal spectrometer was used to measure the spectra of K x-rays produced in thick solid targets of Mg, Al, Si, Cl (NaCl), K (KF), and Ti by 6 AMeV Xe. A spectrum obtained from a combined (metallic) Mg/Al target is

Figure 1. K x-ray spectra of Mg and Al produced by 6 AMeV Xe-ion bombardment.

shown in Fig. 1. The Kα satellites (which arise from $2p \rightarrow 1s$ transitions in the presence of 1 K-vacancy and 1 to 7 L-vacancies) provide a means for assessing the average number of L-vacancies present at the time of K x-ray emission in atoms that have undergone K- plus L-shell ionization. The Kα hypersatellites (which arise from $2p \rightarrow 1s$ transitions in the presence of 2 K-vacancies and 1 to 7 L-vacancies) are also visible in Fig. 1, but their intensities are greatly reduced by absorption in the thick targets because their energies are above the K-

absorption edges. A particularly striking feature of these spectra is the large intensity enhancement of the KL^0 peaks. Most of this enhancement appears to be caused by photoionization resulting from the high flux of Xe L x-rays emitted by the projectile ions in passing through the target.

The relative intensity distributions of the Kα satellites from all the elements examined are compared in Fig. 2. The relative intensities of the Kα satellite peaks, R_n , observed previously with

Figure 2. Comparison of Kα x-ray satellite intensities produced by 6 AMeV Xe impact. Solid curves show binomial distribution resulting from fits of eq.1 to the satellites not marked by cross-hatching.

much lower-Z projectiles¹ were found to be well represented by binomial distributions;

$$R_n = C_n \langle p_L \rangle^n (1 - \langle p_L \rangle)^{8-n} \quad (1)$$

where C_n is the binomial coefficient $8!/(8-n)!n!$, and $\langle p_L \rangle$ is an "effective" (see below) average single L-electron ionization probability for a K-shell

ionizing collision. Those $K\alpha$ satellite intensities shown without cross-hatching in Fig. 2 were fit to the above equation to obtain the $\langle p_L \rangle$ values. The first and last peaks in each distribution were excluded from the fit - the first because of enhancement by photoionization, and the last because of possible distortion by the nearby K absorption edge. The resulting binomial distributions are shown by the solid curves in Fig 2.

Figure 3. The average fraction of L-vacancies remaining at the time of K x-ray emission from solid targets. $\circ$ from present measurements with 6 AMeV Xe; Δ from previous measurements with 2 AMeV Ar.¹

The $\langle p_L \rangle$ values are plotted as a function of the target atomic number in Fig. 3. They increase slightly from Mg to K and are essentially constant thereafter. Also, the present $\langle p_L \rangle$ values for ionization by 6 AMeV Xe (indicated by $\circ$) are almost identical to those obtained previously for 2 AMeV Ar (indicated by Δ).¹ In the absence of mechanisms for filling L-vacancies prior to K x-ray emission, $\langle p_L \rangle$ should represent the L-shell ionization probability averaged over impact parameters that contribute substantially to the K-shell ionization cross section. Simple estimates of this quantity based on the binary encounter approximation lead one to expect it to decrease with increasing target atomic number. The behavior displayed in Fig. 3 clearly contradicts this prediction. On the other hand, one might argue that

$\langle p_L \rangle$ should increase over this region because the L-shell ionization cross section increases with the target Z. However, this point of view fails to account for the fact that $\langle p_L \rangle$ levels off around $Z = 17$ since the L-shell ionization cross section should not reach a maximum until around $Z=46$, where the projectile velocity matches the L-electron velocity. In any case, it is apparent that $\langle p_L \rangle$ reaches a saturation limit in solid targets where the rapid replacement of L-vacancies prior to K x-ray emission prevents it from increasing beyond a value of around 0.48. Further investigation of this intriguing phenomenon is underway.

In the recently initiated investigation of L x-ray emission from highly charged Xe projectiles, the same spectrometer system was used to scan the region from 4000 eV to 5500 eV while directing beams of 6- and 8-AMeV Xe through a variety of targets. Spectra obtained in these measurements are shown in Fig. 4. The broad peaks appearing in spectrum A (obtained using a thick Al target) can be identified with $L\alpha$ and $L\beta$ transitions from several different charge states centered around the equilibrium charge of $43+$. The peaks are very broad, indicating that many different excited state configurations contribute to the spectrum. The rest of the spectra in Fig. 4 were taken with 8 AMeV Xe projectiles, and hence are shifted to higher energies corresponding to the higher equilibrium charge of $45+$. The major point of interest is that the spectra vary from one target to another and even develop discrete structure in the thin carbon targets (E and F). A preliminary analysis of this structure suggests that it is primarily associated with $L\alpha$ transitions in Xe ions which have 1 to 8 L-vacancies and several spectator M-electrons.

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Figure 4. Spectra of L x-rays emitted by highly-charged Xe ions traveling in solid targets;

- (A) 6 AMeV Xe in thick Al,
- (B) 8 AMeV Xe in a thick composite target of Ca and Mg,
- (C) 8 AMeV Xe in $250 \mu\text{g}/\text{cm}^2$ Ni,
- (D) 8 AMeV Xe in $212 \mu\text{g}/\text{cm}^2$ Al,
- (E) 8 AMeV Xe in $280 \mu\text{g}/\text{cm}^2$ C with a $200 \mu\text{g}/\text{cm}^2$ C pre-stripper foil,
- (F) 8 AMeV Xe in $280 \mu\text{g}/\text{cm}^2$ C.

Systematics of Xe Recoil-Ion Charge State Distributions Produced in 8 AMeV Kr Collisions

R. Parameswaran, R. L. Watson, V. Horvat, and G. Sampoll

An amazing array of time-of-flight (TOF) experiments on recoil-ion production in heavy-ion-atom collisions has been conducted in the relatively short span of time since the pioneering work of Cocke.¹ A review of progress in this area is contained in reference.² Despite the immense amount of effort that has gone into the study of recoil-ions, they continue to provide new and interesting information concerning multielectron ionization and exchange processes.

Our recent work in this area has involved measurements of cross sections for noble gas recoil-ion production in electron capture and loss collisions by 8 AMeV Kr^{32+} and Kr^{13+} . A schematic diagram

of the experimental arrangement used in this study is shown in Fig. 1. A beam of 8 AMeV Kr^{13+} is extracted from the cyclotron and passes through a 22° bending magnet prior to entering the gas cell. The charge state of the beam may be changed from $13+$ to $32+$ (the equilibrium charge) by placing a stripper foil in front of the magnet. After exiting the gas cell, the beam passes through another magnet and on to a one-dimensional position sensitive microchannel plate detector. A transverse electric field accelerates recoil-ions out of the gas cell into a TOF spectrometer. Both the recoil-ion TOF and the projectile position are recorded event-by-event.

Figure 2. Two-dimensional TOF data for Xe recoil-ion production in electron loss collisions of 8 AMeV Kr^{13+} .

Figure 1. Schematic diagram of the projectile and recoil-ion charge state analysis system.

A two-dimensional display of data obtained for 8 AMeV Kr^{13+} on Xe is shown in Fig. 2. Projection of the data onto the TOF and projectile position axes show the total Xe recoil-ion TOF spectrum (top) and the Kr projectile charge state distribution (left). It may be discerned from this figure that separate recoil-ion TOF spectra were obtained for collisions in which the projectile lost 0 to 5 electrons and that collisions in which the projectile captured one of more electrons were highly improbable. The data for the $\text{Kr}^{32+} + \text{Xe}$ system yielded separate recoil-ion TOF spectra for collisions in which the projectile captured 0 to 4 electrons and revealed that collisions in which the projectile lost one or more electrons were highly improbable.

Figure 3. TOF spectra of Xe recoil-ions produced in electron loss collisions of 8 AMeV Kr^{13+} and electron capture collisions of 8 AMeV Kr^{32+} .

The TOF spectra for each of the above mentioned cases are shown in Fig. 3. The spectra for pure ionization (in which case the projectile charge does not change) are typical of large impact

parameter collisions involving only outer-shell electrons. Electron loss collisions, on the other hand, involve impact parameters $\approx 0.3 \text{ \AA}$ - the approximate outer-electron radius of Kr^{13+} , and electron capture collisions involve capture to the L-shell at impact parameters around $0.08 \text{ \AA}$ - the approximate outer-electron radius of Kr^{32+} . The TOF spectra for the capture and loss channels are characterized by bell shaped recoil-ion charge state distributions, reflecting the fact that once the O- and N-shells of Xe are penetrated, many-electron processes dominate.

An analysis of the recoil-ion charge state distributions brought to light several interesting questions. First of all, why are the average recoil-ion charges so different for the two cases studied (e.g. $\langle q \rangle \approx 10+$ for loss collisions of Kr^{13+} and $\langle q \rangle \approx 25+$ for capture collisions of Kr^{32+})? Qualitatively, the answer to this question is fairly obvious. Since the projectile charge is greater and the average impact parameter smaller in the capture-collision case, the number of ionized electrons should be substantially larger. Moreover, capture of one or more L-electrons opens up Auger channels that are not available in the loss-collision case. The Auger cascade resulting from one L-vacancy, by itself, can lead to a final charge of $8+$. Nevertheless, as will be discussed below, the average recoil-ion charges for the capture collisions do appear to be much higher than expected from the results of previous studies.

Figure 4. The widths (FWHM) of the Xe recoil-ion charge state distributions as a function of the number of electrons captured or lost by the Kr projectile.

The second question concerns the widths of the charge state distributions. It is reasonable to assume that the average impact parameter steadily decreases as the projectile captures or loses more and more electrons. Therefore, the average recoil-ion charge and the width of the charge state distribution should steadily increase with increasing numbers of electrons captured or lost. The charge state distributions for loss-collisions of Kr^{13+} are in accord with both of these expectations, as may be seen from the TOF spectra in Fig. 3 and the distribution widths shown in Fig. 4. However, the distribution widths for capture-collisions of Kr^{32+} display just the opposite trend.

Figure 5. Final charge of Xe recoil-ion as function of number of N- and O- shell electrons ionized in collision. Number of L-shell electrons captured by the projectile is given by k .

The decline in the distribution width as a function of the number of electrons captured is apparently related to limitations that are imposed on the subsequent Auger cascades by the number of outer-shell electrons ionized in the collision. Consider the final charge of a recoil-ion as a function of the number of N- and O-shell electrons ionized (I) and the number of L-electrons captured (k), as is shown in Fig. 5. This figure has been constructed under the assumption that Auger decay will occur whenever possible (i.e. that the Auger yields are 100%). Experimentally, the average final charge for the one-electron capture case ($k = 1$), was found to be $20+$, and according to Figure 5 this implies that, on average, 16 electrons were ionized from the N- and

O-shells. The additional 4 units of charge result from the Auger cascade initiated by the single L-vacancy; when the L-vacancy is filled, 2 M-vacancies are created, etc. This process ends with 4 vacancies in the N-shell because all of the O-shell electrons already have been ionized in the collision. When I exceeds 22 in the $k = 1$ case, the Auger cascade must terminate at the M-shell and the rate of increase in the final charge goes down (on average) by a factor of 2. Similarly for $k = 2, 3$, and 4, the number of Auger decays becomes limited by the number of remaining M-shell electrons when I exceeds 18, 14, and 10, respectively. As may be discerned from Fig. 5, an I value of 16 gives final charges that are in perfect agreement with the average experimental charges ($20+$, $24+$, $27+$, and $29+$ for $k = 1$ through 4, respectively). If it is assumed that the distribution of ionized electrons is not very sensitive to the number of L-electrons captured and has a width of 8 units (the same as for $k = 1$), then Fig. 5 shows that this ionization width projected onto the final charge axis predicts final charge distribution widths of 7, 5, and 4 units for $k = 2, 3$, and 4. This rather good agreement between the predicted widths and the experimental widths lends credence to the hypothesis that limitations on the number of Auger decays causes the width of the charge distribution to decrease with increasing k .

Returning now to the question of the magnitude of the average charge produced in the electron capture collisions, it is informative to compare the results of the present measurements with those performed by Kelbch *et al.* [3] using 9 AMeV U^{65+} on Xe. The charge state distributions are shown in Fig. 6. It is quite surprising to find that the charge state distributions for these two collision systems are so similar even though the ionic charge of the U projectile is over a factor of two larger than that of the Kr projectile. This observation may simply mean that the range of impact parameters required for electron capture to U^{65+} is significantly larger than for Kr^{32+} , and that (coincidentally) the same number of outer-shell electrons are ionized in both cases. Although the radii of the innermost unfilled subshells

are about the same for both Kr^{32+} (2p) and U^{65+} (3d), the larger ionic charge of the latter might cause the capture probability to peak at larger impact parameters. The apparent ionization limit does not appear to be connected with the shell structure of the Xe atom since the total ionization energy (which is approximately 9.3 keV for $q = 25+$) varies fairly smoothly with the number of electrons removed.

It is planned to more fully characterize this effect by carrying out a systematic study of recoil-ion production in electron capture and loss collisions employing equal-velocity projectiles ranging from He^{2+} to Xe^{45+} . In this work, the dependence of

recoil-ion production cross sections on projectile charge and energy, and target atomic number will be investigated with the ultimate goal of establishing a new semiempirical method for their prediction.

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Figure 6. Comparison of the Xe recoil-ion charge state distributions produced in electron capture collisions by 8 AMeV Kr^{32+} (present data) and 9 AMeV U^{65+} . [3]

Orientation Dependence of Cross Sections for Multielectron Ionization of CO Molecules in 96 MeV Ar¹⁴⁺ Collisions

V. Horvat, O. Heber, G. Sampoll, R. Parameswaran, and R. L. Watson

The dependence of ionization and capture cross sections for molecules on the orientation of the internuclear axis relative to the beam direction has been a topic of long-standing experimental and theoretical interest. It was recognized as early as 1960 by Tuan and Gerjuoy¹ that interference of scattering amplitudes from the two atomic centers in the hydrogen molecule could lead to orientation-dependent cross sections for electron capture by protons. More recent theoretical work on this interference phenomenon has been performed by Bottcher,² Deb *et al.*,³ Shingal and Lin,⁴ and Wang *et al.*^{5,6} It has also been shown that anisotropies in the cross sections for producing highly-charged diatomic molecules by pure ionization can arise from geometric effects associated with the cylindrical symmetry of the electron distribution.⁷

The first experimental verification of the interference effect was recently announced by Cheng *et al.*⁸ A jet of deuterium molecules was crossed with a beam of O⁸⁺ ions having energies of 1, 4, 10 and 16 MeV. By applying an extraction field perpendicular to the beam axis, D⁺ ions resulting from dissociation of D₂ following electron capture collisions were projected onto a 2-dimensional position sensitive (resistive anode) microchannel plate detector. Simultaneous measurement of the time-of-flight allowed reconstruction of the three-dimensional velocity distribution. A strong dependence of the cross section on the angle between the beam axis and the internuclear axis was observed. The results showed that the deuterium molecules involved in electron capture collisions were much more likely to be oriented with their axes perpendicular to the beam than parallel to the beam.

A severe limitation associated with the application of a resistive anode MCP to the simultaneous position determination of ion-pairs is the relatively long time required to collect and process

the position signals. Because of this, dissociation events for which more than one ion is detected generate summed position signals that distort the velocity distribution and complicate its direct comparison with the predictions of theory. Recently, a new optical detection system (described in report beginning on p. IV-102) has been employed to overcome this limitation and to extend the investigation of molecular orientation effects to the 96 MeV Ar¹⁴⁺ → CO collision system. A brief description of the analysis and results obtained for the dissociation reaction CO²⁺ → C¹⁺ + O¹⁺ is given below.

The experiment required the measurement of two times-of-flight (TOF) and two positions for each acceptable event. The TOF measurements were accomplished with two time-to-amplitude converters - TAC1 determined the TOF of the first-arrival ion and TAC2 determined the time difference between the first-arrival ion and its dissociation partner. The ion positions were recorded simultaneously by a CCD camera viewing the phosphor screen behind the ion detector (see report beginning on p. IV-102). The position sensitivity was determined to be 5.18 pixels/mm in the x-direction and 3.02 pixels/mm in the y-direction. The slopes of the time scales of the two TACs were calibrated using an ORTEC model 462 time calibrator. The intercept of the TAC1 calibration was obtained from the photon peak appearing in the singles TOF spectrum, while the intercept of the TAC2 calibration was established by measuring the delay (17.8 ns) imposed on the start signal to prevent starting and stopping TAC2 with the same signal. A comparison of the TOF spectra for the first and second ions is shown in Fig. 1. It can be seen that the positions of the various peaks are the same in both spectra, thereby confirming the accuracy of the time calibrations.

The overall objective of the analysis procedure was to reconstruct the 3-dimensional velocity vectors

Figure 1. Time-of-flight spectra for the first and second ions of CO dissociation product pairs detected in coincidence.

Figure 2. Calibration curve relating to TOFs of C^{1+} and O^{1+} to their z-velocity components.

of both ions for each detected event from the measured TOFs and positions. The z-component of velocity was determined directly from the TOF using the calibration curves shown in Fig. 2. These calibration curves were constructed by calculating the TOFs for C^{1+} ions having energies between 0 and 40 eV and the TOFs for O^{1+} ions having corresponding energies using the electrostatic lens program

SIMION.⁹ In comparing calculated and measured TOFs for Ar ions, it was found that SIMION yielded values that were systematically larger (by up to 2.8%) than the measured values. The calibration curves shown in Fig. 2 have been corrected for this discrepancy. Since the velocities of the C and O ions are related by the law of conservation of momentum,

$$v_0/v_C = -m_C/m_0 = -0.75, \quad (1)$$

the velocity of the oxygen ion in Fig. 2 may be obtained by multiplying the velocity of the corresponding carbon ion by -0.75.

Figure 3. Data for $C^{1+} + O^{1+}$ displayed on t_1 v. t_2 plot. Solid curve through center of data region is calculated t_1 - t_2 calibration curve.

Analysis of the data was restricted to $C^{1+} + O^{1+}$ ion pairs for which two and only two spots were detected by the CCD camera. A 2-dimensional representation of the data falling within the TOF region for $C^{1+} + O^{1+}$ ion pairs is shown in Fig. 3, superimposed upon the first-ion TOF (t_1) versus second-ion TOF (t_2) calibration curve extracted from Fig. 2. The scatter of the experimental data about the calibration curve reflects the finite time resolution of the experiment. In order to insure that conservation of momentum was upheld throughout the analysis, each experimental data point was replaced by the pair of t_1 , t_2 values belonging to the closest point on the calibration curve.

The starting coordinates (x_0, y_0) for each detected dissociation event may be expressed in terms of the final coordinates of the product ions by utilizing the law of conservation of momentum;

$$\begin{aligned} x_0 &= (w_1 x_1 + w_2 x_2) / (w_1 + w_2) \\ y_0 &= (w_1 y_1 + w_2 y_2) / (w_1 + w_2) \end{aligned} \quad (2)$$

where $w_1 = m_1/t_1$ and $w_2 = m_2/t_2$. The velocity components were calculated using expressions derived from eq. (2). In the case of the x-velocity components,

$$\begin{aligned} v_{1x} &= m_2(x_1 - x_2) / (m_1 t_2 + m_2 t_1) \\ v_{2x} &= -m_1(x_1 - x_2) / (m_1 t_2 + m_2 t_1). \end{aligned} \quad (3)$$

Once the velocity components were determined, the kinetic energies of the product ions and the angle between the molecular axis and the beam axis (α) could be obtained.

Figure 4. Total kinetic energy distribution for the dissociation reaction $\text{CO}^{2+} \rightarrow \text{C}^{1+} + \text{O}^{1+}$.

The resulting total kinetic energy distribution for the $\text{C}^{1+} + \text{O}^{1+}$ product ions is shown in Fig. 4. The overall shape of this distribution is similar to the one obtained in our earlier work by a procedure that involved a rather complicated transformation of the time-difference distribution,¹⁰ but the average total kinetic energy (12.4 eV) is 38% lower.

With regard to the angular distribution, it should be noted that when the ionization cross section is independent of the orientation of the molecule, the number of dissociation events with angles between α and $\alpha + d\alpha$ is proportional to $\sin \alpha$. Therefore, a histogram of ΔN versus α with equally spaced

Figure 5. Angular distribution for the double ionization of CO by 97 MeV Ar^{14+} projectiles.

angular bins will exhibit a maximum centered around 90° . In order to eliminate this effect, the angular distribution obtained for CO^{2+} is shown in Fig. 5 in the form of a graph of $\Delta N / (\Delta \cos \alpha)$ versus α . In this form, an isotropic distribution will appear as a line with zero slope. It is apparent that the present results indicate the cross section for double ionization of CO by 97 MeV Ar^{14+} ions is anisotropic with considerably more ionization events occurring when the CO axis is perpendicular to the beam axis. Further work aimed at verifying these results and providing data for higher charge states is in progress.

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Total Kinetic Energy Release in Dissociative Electron-Capture Collisions of 97 MeV Ar^{14+} with CO Molecules

G. Sampoll, R. L. Watson, O. Heber, V. Horvat, and R. Parameswaran

The analysis of data from an experimental investigation of the total kinetic energy (TKE) released in dissociation reactions resulting from electron capture collisions of 97 MeV Ar^{14+} with CO has been completed. In these experiments, three parameters were recorded for each detected event; the first-ion time of flight (TOF1), the second-ion time of flight (TOF2), and the exit charge of the projectile. The projectile charge was measured by adding a charge dispersing magnet behind the gas cell and employing a position sensitive microchannel plate detector to determine the deflection of the projectile.

The TOF spectra obtained for one- and two-electron capture collisions are compared in Fig. 1 with the pure ionization spectrum obtained previously.¹ It is readily apparent that the electron capture collisions greatly accentuate the higher charge states, just as they do in atomic targets. Perhaps a more interesting observation is that the most highly charged ions produced are C^{4+} and O^{6+} . Thus, it is evident that even in the two-electron capture collisions, where the captured electrons come primarily from the K-shells of the C and O ions, these K-shell vacancies do not survive the dissociation process. This means there must be sufficient electron exchange between the departing ions to insure that each escapes with at least two electrons in states that evidently do not undergo further autoionization.

Figure 1. Comparison of TOF spectra of CO dissociation products produced in (a) pure ionization, (b) one-electron capture, and (c) two-electron capture collisions by 97 MeV Ar^{14+} . Multicharged CO molecular ions produced in one-electron capture collisions.

Figure 2. Total average kinetic energies for the dissociation of CO as a function of the ion-pair charge product for pure ionization ($\square$) with $q_C \geq q_O$ and (∇) with $q_C < q_O$, one-electron capture ($\circ$) with $q_C \geq q_O$ and (Δ) with $q_C < q_O$, and two-electron capture ($\blacklozenge$) with $q_C \leq q_O$. The solid line shows the point-charge Coulomb.

Analyzable Δt distributions were obtained from the electron-capture data for 17 ion pairs ranging from $C^{1+} + O^{1+}$ to $C^{4+} + O^{4+}$ and $C^{3+} + O^{6+}$. The average TKE's for electron capture collisions are compared with those obtained previously for pure-ionization collisions in Fig. 2. The solid line shows the Coulomb energy for point-charge ions separated by the neutral molecule equilibrium bond length. It was noted previously that all of the experimental average TKE's for pure ionization collisions exceed the point-charge Coulomb energies. Although it is difficult to interpret this result directly in terms of the molecular states involved because theoretical potential energy curves are not currently available for any molecular system beyond $Q = 2$, nevertheless it can be generally concluded that the states populated in these collisions are highly repulsive. Classically, this means that the two ions are not fully screened by the electrons that remain after the collision since the point-charge Coulomb energies (which are calculated from the ionic charges and therefore assume full screening) are significantly smaller than the experi-

mental average TKE's. In the limit of totally stripped dissociation product ions, however, the TKE must converge to the point-charge Coulomb energy. In fact, the pure ionization data for CO do appear to be converging with the Coulomb energy at the highest values of the ion-pair charge product $q_1 q_2$.

The TKE's obtained for electron capture collisions are substantially larger than those for pure ionization collisions. Presumably this result stems from the increased repulsion associated with the removal of inner-shell electrons in the collision process. Another noteworthy feature is that the TKE's appear to be systematically larger for ion pairs where the charge of the oxygen ion is greater than the charge of the carbon ion.

The implications of the above results are not yet fully understood, and further work will be required for a more complete interpretation. First of all, we plan to verify these TKE values by repeating the measurements with the new optical detector system. Since this detector system provides all the information needed to compute the three-dimensional velocities of both ions, the TKE's may be obtained by methods that are much more direct and less prone to uncertainty than the complicated transformations of Δt distributions used until now. Similar experiments will be performed with the NO molecule, whose bonding characteristics are quite different from those of CO. Additionally, measurements will be carried out with other projectiles and at other energies to delineate the effects these parameters have on the distribution of molecular excited states populated in heavy ion collisions.

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A Method for Simultaneous Position and Time-of-Flight Determination of Ion-Pairs from the Dissociation of Multicharged Molecular Ions

O. Heber, V. Horvat, G. Sampoll, R. Parameswaran, and R. L. Watson

Detailed investigation of the dependence of cross sections for the dissociative ionization of diatomic molecules on the orientation of the internuclear axis requires the ability to identify both dissociation product ions and to determine the initial velocity vector of at least one of them. An ion-ion coincidence time-of-flight (TOF) technique, made possible by the excellent fast timing properties of microchannel plate detectors, has been utilized in our past work to identify both ions produced in binary dissociation events of multicharged molecular ions.^{1,2} Over the past two years, considerable time and effort have been invested in attempts to employ a two-dimensional microchannel plate detector with a resistive anode to simultaneously measure the times-of-flight and positions of both ions from binary dissociation events. Unfortunately, it was found that time difference and pulse height division methods were too slow to provide separate position signals for both ions from the same binary event. Under this circumstance, the resulting position signal is actually a superposition of the signals generated by each ion and hence cannot be used for the determination of the three-dimensional velocity vector of either.

In an effort to overcome this problem, we have explored the possibility of applying optical methods to the simultaneous position determination of both ions. The basic idea was to couple a set of microchannel plates in a chevron configuration with a phosphor screen and determine the ion positions by visually recording the light spots marking the points of ion impact with the MCP using a CCD camera.

A set of 75 mm diameter microchannel plates coupled through a fiberoptic substrate to a type P20 phosphor screen was obtained from Galileo Electro-Optics Corporation. This MCP assembly was attached to a TOF spectrometer system incorporating a gas jet and a uniform ion-extraction field, as shown in Fig. 1. The phosphor screen was viewed from

Figure 1. System for simultaneous position and TOF measurement of ion-pairs produced in dissociative ionization of diatomic molecules.

outside the vacuum system through a lucite viewport by a high resolution CCD camera (Javelin Electronics model JE-7442). When an ion strikes the microchannel plates, a jet of secondary electrons is produced and accelerated through a potential difference of 3000 V onto the phosphor screen. This results in the emission of a bright spot of yellow-green light which is detected by the CCD camera. The time of decay to 10% of the initial brightness for spots produced in type P20 phosphors is 0.2 ms. The number of pixels with intensities above the CCD noise averages around 2 per detected ion. Fast timing signals are obtained from the back of the second MCP and used for the TOF measurement of each ion.

The CCD camera video output consists of 576×260 pixel coordinates and their intensities for each frame. The video signals are sent to an IBM compatible PC-386 computer where they are analyzed

via a frame threshold suppresser (FTS) developed and constructed by the Laboratory Computer Section of the Weizmann Institute of Science, Rehovot, Israel. The FTS digitizes the video signal with a 10Mhz, 8 bit ADC and compares each pixel amplitude to a preset digital threshold. The amplitude and coordinates (row and line) of each accepted pixel are stored in the internal 8 Kbyte memory of the FTS where they can be read by the PC-based data acquisition system. This selection procedure considerably reduces the time required to process a video signal.

The PC-based (multiparameter) data acquisition system is interfaced to a CAMAC crate controller. The present application required considerable modification of the data acquisition software. In particular, algorithms were added to read the data from the FTS. Since the FTS does not have installable drivers, the data acquisition program must address the FTS registers directly. In order to utilize the library of CAMAC-related routines that came with the CAMAC-PC interface card, a set of FORTRAN-callable ASSEMBLER routines were written to accomplish this task. In addition, special pattern recognition algorithms were developed to identify spots from arrays of lit pixels, determine total spot intensities, and calculate the center-of-intensity coordinates. Also, checks are performed to prevent spot carry-over from one frame to the next. The data acquisition system accomplishes all the necessary on-line operations within the 16 ms cycle period of the CCD camera.

A test of the system was conducted using Ar^{1+} recoil-ions and $\text{C}^{1+}/\text{O}^{1+}$ ion pairs from the dissociation of CO^{2+} produced in collisions with 97 MeV Ar^{14+} . A plot of the number of detected Ar^{1+} ions versus their x and y position coordinates on the phosphor screen is shown in Fig. 2. Since the Ar^{1+} ions have very little kinetic energy, their position distribution mirrors the profile of the gas jet across the interaction region defined by the beam. The beam axis is outlined by the low intensity ridge in Fig. 3, which is caused by collisions with background gas atoms from the jet. A (combined) position

Figure 2. Position distribution of Ar^{1+} ions on the phosphor screen.

distribution of C^{1+} and O^{1+} ions obtained in a first-attempt application to the study of dissociative ionization of CO molecules is shown in Fig. 3. In

Figure 3. Position distribution of C^{1+} and O^{1+} ions produced in the dissociation of CO^{2+} .

this case, the position distribution reflects the substantial amounts of kinetic energy released in the dissociation process and shared by the C and O ions. A preliminary analysis of the flight times and positions of the individual ions for each ion pair event has been performed and the results are described in the report beginning on p. IV-97.

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Studies of the Interaction of Multiply-Charged Ar Ions with Surfaces

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This past year, we completed our work on light emission from the interaction between multiply-charged slow, heavy ions and surfaces. The study of light emission was primarily from NaCl targets with Ar as a projectile. The main focus of the work has been to look for possible electronic contributions to the sputtering process and to determine the mechanism by which ions neutralize as they approach and interact with the surface. The ground work, experimental setup and some preliminary results of our previous work are discussed in Ref. [1].

In brief, our apparatus was setup in a general purpose ultra high vacuum (UHV) scattering chamber that is located on the beam line from the ECR source for atomic and surface science experiments. A description of the beam line can be found in Ref. [2]. Light emission from the surface of the target was observed with a JARELL-ASH (Model 82-000) series Ebert Scanning Spectrometer which was coupled with a C31034 GaAs photomultiplier tube by Burle. The C31034 is a low noise tube especially suited for single photon counting with a quantum efficiency that is optimized for wavelengths around 600 nm. For even lower background noise, the tube was cooled to -30°C with a solid state cooling device, which also needed external water cooling for better heat exchange. We used a -5°C alcohol + H₂O based solution circulating in the heat exchanger. The phototube was operated with negative high voltage (-1750 VDC). Output signals from the anode were amplified by an Ortec Model 579 Fast Filter Amplifier and then sent to a PS Model 715 Five

Channel Timing Discriminator. The discriminator level was adjusted to be above the noise of the amplifier but below the voltage output level from the amplifier corresponding to a single photo-electron striking the photo-cathode. The discriminator output signals were sent through a logic converter and then counted by a Tennelec Model TC-532 Counter. The spectrometer was used in a mode where a single transition was observed at a fixed grating angle. The grating angle was adjusted manually to look at a wavelength of 589.3 nm (the middle of Na D lines). The calibration of the JARELL-ASH spectrometer coupled with the phototube was done with a sodium vapor lamp. During the experiments the light sensitivity of the system was checked against a 100 W semi-opaque light bulb kept at 22.00 VDC. The light output of the bulb was constant but very sensitive to changes as small as ± 0.01 VDC. A detailed schematic view of the apparatus is discussed in Ref. [1].

The main difference in the setup from last year is the way the target was heated and supported. The NaCl target was heated constantly to 400°C, both to keep the target surface clean and to increase its conductivity. The Omegalux Sub292 high temperature high vacuum heaters manufactured by Spectra-mat Inc. that we originally used, were extremely fragile and unreliable. We were able to make a reliable heater using 0.0125 cm diameter tungsten wire about 100 cm long with a resistance of about 6 Ω . The tungsten was rolled into 2 mm diameter spirals and fixed to the back of the oxygen

free high conductivity copper target holder with Sauereisen paste #1. This particular paste is made from sodium silicate and is water based. It has very poor electric and excellent heat conductivity. Other important characteristics were that it had a similar coefficient of expansion as copper and a low outgassing rate in an UHV environment once it is baked.

For the target, we used a fine mesh copper grid (0.5 mm grid spacing) upon which Sodium Chloride granular crystals were pressed at a pressure of 20,000 lbs, using a pellet die. The result was a target 2.54 cm in diameter with a smooth surface and 0.5 mm thick. Due to the pressure the small granules formed a solid target which could be mounted on the target holder without losing any material. This method provided us with enough heat and electric conductance, so that the target would be heated uniformly and static buildup due to incoming positively charged ions would be minimized at the surface of the sample.

An incident kinetic energy of 48 keV was chosen to study the potential energy dependence. In Fig. 1, we show the light yield as a function of charge state for incident beams of charges 4^+ to 11^+ .

Figure 1. NaCl light yield as a function of the incident ion potential energy. All of the incident beams had a fixed kinetic energy of 48 keV.

The relative yield for each data point has been normalized to the number of incident Ar atoms on the target. The overall scale used in the figure is arbitrary. The uncertainties for the data points were estimated to be at 6%. This estimate includes contributions from background, statistics, beam integration, geometry and possible surface effects. It is clear from Fig. 1 that contrary to the silver case,³ the light yield does change with increasing ionic charge state of the beam. These results tend to agree with Tribble et. al.,⁴ in which there is an increase by a factor 1.30 from Ar^{4+} to Ar^{12+} .

Figure 2. NaCl light yield as a function of the incident ion kinetic energy. The line through the data is a quadratic function fitted by the method of least squares, with χ^2 per degree of freedom of 0.83.

The kinetic energy dependence of the light yield was studied over a range of incident energies from 8 keV to 99 keV. The results of the measurements as a function of incident energy are shown in Fig. 2. The data were taken with several different charge states as noted in the figure. We normalized the data such that only the kinetic energy dependence remained; to remove the potential energy dependence all points were normalized with respect to the Ar^{8+} @ 48 keV. In the Ag case,³ the light yield showed a steady and substantial increase (nearly a factor of 10) over the same energy range. Based upon the current set of data the NaCl results show distinctly different characteristics.

During this year, we began carrying out computer simulations of atomic collisions in crystalline targets to emulate sputtering from the surface of a Ag target bombarded by Ar atoms, with the MARLOWE program, which simulates atomic collisions in crystalline targets using the binary collision approximation. The program tracks an energetic atomic projectile, either from an external beam or from an interior site, into a target and follows the slowing-down of the primary particle and (if desired) of all target particles which are displaced from their lattice sites, until they either leave the target or fall below a selected low energy value. The particle trajectories are constructed as a series of binary encounters between the projectiles and the initially stationary target atoms. Elastic scattering is governed by one of several different repulsive interatomic potentials. Inelastic (electron excitation) effects are included in a low-energy (< 25 keV/amu) approximation Ref. [5].

We were hoping to be able to develop a relation between the light emission process and the K.E. of the sputtered atoms from the surface to explain the nearly tenfold increase in sputtered Ag atom light yield from 8 keV to 99 keV Ar incoming energy that was discussed in last year's report. The hypothesis was that the light output which was seen, was mainly emitted by the more energetic (i.e. 50 eV and above) sputtered Ag atoms.

In Fig. 3 we show simulated sputtered Ag atom energy distributions from 0 to 800 eV, with incoming Ar atoms at 8, 16, 24, 48 and 99 keV. As the figure shows, the area under the curve from 50 eV to 800 eV does not show much change from 8 to 99 keV. Certainly not a significant increase. So we can conclude from these results that either our assumption was incorrect or the program is not adequately describing the high energy tail. Most likely, the origin of the light emission charge with kinetic energy is more complicated than the simple picture that we discussed in the previous report.

Electron emission has been used to study the charge neutralization process on metallic targets as a function of ion charge for kinetic energies ranging

from a few hundred eV to several keV.^{6,7} The yield of emitted electrons is observed to depend on both the kinetic energy and the potential energy of the incoming ion. The neutralization of the incoming ion as suggested from these experiments occurs through a transfer of charge from the surface atoms to the incoming ion via a series of resonant transfer or Auger transfers of electrons accompanied by Auger deexcitation in the surface and incident atoms Ref. [8, 9].

We hope to repeat the Ag and NaCl experiments, this time measuring the electron emission yield and energy spectra. Studies have been performed on Ag targets which will help us calibrate our setup Ref. [10].

There usually is a large peak of low-energy (≤ 20 eV) emergent electrons and subsidiary peaks at higher energies due to Auger transitions for the Ag target. Their energies should vary from 0-1000 eV. Our electron spectrometer, Model AC-902 from Comstock Inc. can be modified to accept this range of energies. The setup inside the UHV scattering chamber will be very similar to previous experiments, except for the inclusion of the AC-902 in the system. The area surrounding the Comstock spectrometer will be properly shielded from stray magnetic fields.

One advantage of a metal target is its high electrical conductivity. As the ions from the ECR approach and embed themselves in the target, their positive charge will very rapidly dissipate to ground (of the order of one over the plasma frequency $t = 10^{-16}$ s). This of course is not possible with an insulating target such as NaCl. Ion impact on poorly conducting materials will generally result in charge buildup on the bombarded surface. The magnitude of this effect depends on such parameters as the resistivity of the sample and the P.E., the K.E. and the angle of the incident particle. This effect is destructive in two ways. First, charging the surface makes controlled bombardment of the surface no longer possible. Second, any voltage buildup on the surface of the target will seriously distort the yield and energy spectrum of the secondary electrons. To

1000 Ar@8keV on Ag target. 7733 Ag sputtered.

1000 Ar@16keV on Ag target. 7940 Ag sputtered.

1000 Ar@24keV on Ag target. 7189 Ag sputtered.

1000 Ar@48keV on Ag target. 6635 Ag sputtered.

1000 Ar@99keV on Ag target. 4734 Ag sputtered.

Figure 3. Computer simulations of sputtered Ag atom energy distributions from 0 to 800 eV, induced by 1000 incoming Ar atoms at 8, 16, 24, 48, and 99 keV.

counteract this problem we plan to use an electron gun model FRA-2X1-2 from Kimball Physics to neutralize the surface. This particular electron gun is capable of emitting modest beam currents at energies as low as 5 eV, and currents as high as 220 μ A. With this instrument the surface of the sample could be flooded with low energy electrons (up to 10 eV), and this should prevent the target from charging up. A second method is also available, a simple hot filament near the surface would have the same effect.¹¹ In either case, we need to study the effect of this electron cloud on a metal target first by comparing the electron spectrum from a metal target with and without the electron cloud.

Unlike the previous set of experiments on light emission, the data acquisition will need to be computerized. The AC-902 needs to be stepped in voltage so that it can cover the whole range of electron energies. Data must be recorded during each voltage step. These tasks are well suited for a standardized data-acquisition system, such as CAMAC, attached to a computer. A 286-8 MHz IBM PC compatible with a 16-bit AT bus will be used in this setup. Also a DSP Technology, Inc. CAMAC crate controller model 6002 and a plug-in card model PC004, will provide us with a high speed DMA interface between the computer and the instrument modules installed in the CAMAC crate. The programming phase of the CAMAC interface computer code is well underway. The language used is Microsoft FORTRAN Ver. 5.0. The program is able to run the CAMAC crate as well as display the data live and store them. It was written in such way so that minor changes can be made with minimal effort while the experiment is running.

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Measurements of Atomic Ground Term Metastable Lifetimes of Highly-Charged Ions

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We have installed a Kingdon ion trap in the target chamber of the low-energy ultra-high vacuum beam line attached to the ECRIS, and used it for the first measurements of lifetimes of magnetic dipole (M1) and electric quadrupole (E2) transitions in the ground electronic terms of highly-charged ions. The Kingdon trap is electrostatic in nature, with a geometry similar to a Geiger tube, consisting of a cylinder and coaxial central wire, and two end plates. When the caps and cylinder have a positive potential relative to the central wire, positive ions can orbit stably for many hundreds of milliseconds at uhv pressures. To accomplish ion capture, an ion beam with selected mass-to-charge ratio is extracted from the ECRIS at a potential near the trap cylinder potential, typically 3.5 kV. The slowed ions pass through the trap, and are captured when the potential of the central wire is suddenly (in a few hundred nanoseconds) reduced to zero. The ion beam is then deflected by up-stream plates.

value. Some of the ions emerge through an aperture in the cylinder and are detected using a microchannel plate assembly (see Figure 1). By making these measurements as a function of ion storage time, it is observed that the ion number decreases exponentially, with a time constant that depends on the residual gas pressure in the chamber.

Since the goals of the research were to observe "forbidden" transitions and to measure the lifetimes of the emitting states, an optical system with a low noise photomultiplier detector and interference filter for wavelength selection was added, as shown in Figure 1. Photons were counted during the ion storage intervals, and at the appropriate wavelengths corresponding to transitions between levels of ground state terms, were found to decrease exponentially with time. For the inaugural measurements, we studied ions of argon: the $2p^5 \ ^2P_{3/2} - 2p^5 \ ^2P_{1/2}$ decay of Ar^{9+} near 553 nm, the $2p^4 \ ^3P_2 - 2p^4 \ ^3P_1$ decay of Ar^{10+} near 693 nm, and the $3p^4 \ ^1D_2 - 3p^4 \ ^1S_0$ decay of Ar^{2+} near 519 nm (see Figure 2). Measurements were made as a function of pressure of typical residual gases, to correct for the effects of collisional quenching of the metastable states. The measured lifetimes, after appropriate corrections, are summarized in Table 1.

Lifetimes of these and similar states are useful with other information to obtain electron densities and temperatures of astrophysical and laboratory plasmas. Such lifetimes have been the subject of extensive calculations, but have never before been measured for ions with charge states higher than $3+$. Our technique is potentially applicable to any element or charge state that can be extracted with sufficient current from the ECRIS. Measurements on astrophysically-important iron and nickel transitions are planned after the completion of improvements in technique.

Figure 1. Apparatus configuration

Once ions are captured, they are confined for a chosen interval and then dumped by letting the wire potential rise slowly (milliseconds) to its original

Table 1. Lifetime measurement results with random and systematic error estimates. The systematic shift is due to pressure independent ion storage limitations.

Level	Lifetime (in ms)	
	Exp.	Theory
$\text{Ar}^{10+}, 2p^4 \ ^3P_1$	14.8 (± 1.1 , $-.05$)	15.08 ^a
$\text{Ar}^{9+}, 2p^5 \ ^2P_{1/2}$	8.53 (± 0.24 , -0.17)	9.43 ^a
$\text{Ar}^{2+}, 3p^4 \ ^1S_0$	159.7 (± 9.7 , -38.4)	152.8 ^b
		149.4 ^c

^a(ref 1), ^b(ref 2), ^c(ref 3)

Figure 2. Level diagrams.

**SUPERCONDUCTING CYCLOTRON
AND INSTRUMENTATION**

K500 Development and Operations

D. P. May, G. Mouchaty, and G. J. Kim

During the 1992-93 reporting period, the operation of the K500 has become more reliable at higher energies for longer periods. Also, it was found that a main-coil repositioning, a raising of the K500 superconducting coil, was necessary in order to run the $q/m = 1/2$ beams again ($E_{TOT} > 50$ AMeV). After this repositioning, trial runs with 62.5, 67.5, and 70.0 AMeV deuterons were successful. Also during the reporting period, the highest total energy beam to date, 40 AMeV $^{63}\text{Cu}^{21+}$, was developed. Unfortunately, the experimenters could not effectively use the low beam current (150 epa), but it did serve to illustrate the ability of the source to run long-term high-charge-state beams from solid materials.

K500 Reliability and Stability

Cyclotron reliability has increased substantially due mainly to an increase in deflector reliability. Deflector development is described elsewhere in this progress report,¹ but the result has been that Macor® insulators with glued titanium ends are used for the first electrostatic deflector E1. Also a new conditioning procedure has been worked out. It involves conditioning slowly with no magnetic field and then with magnetic field using a flow of oxygen gas introduced through the rear of the deflector housing. The voltage on the deflector is incremented as drain or microsparking is reduced. This is similar to the conditioning procedure of the sapphire insulators with argon gas except for the period of no-field conditioning.

Other improvements include replacement of one of the broken Cryotorr 7 cryopumps on the injection line with a more reliable Cryotorr 8, replacement of the soldered insulator feed-throughs for the inflector with O-ring sealed ones, and replacement of the sliding-pin gas valves on the ECR with more precise and reliable sapphire-seated gas valves. Also a large improvement in the stability of the beam resulted from the replacement of the ECR analysis-magnet

power supply with one with better regulation. It was found that the old supply would randomly go into unstable modes which were not seen on the control system or even on the current meter of the supply, and much time was wasted trying to "stabilize" the ECR as a consequence.

Through the first half of the reporting period and including hours scheduled for beam development, unscheduled maintenance took up 16.5% of the scheduled time, deflector maintenance representing 8.5% (262.75 hrs). In the second half, unscheduled maintenance was 9.8% of the scheduled time with deflector maintenance representing 2.6% (62.5 hrs). For the period of April 1, 1992 to March 31, 1993, the operational time is summarized in Table 1 while the scheduled time is listed in Table 2.

Main-Coil Repositioning and Higher Energies

In attempting to tune a 65 AMeV deuteron beam for an experiment in Dec. 1992, it was found that beam extraction was difficult and the ultimate extraction efficiency extremely low. Going down in energy, it was found that a 55 AMeV deuteron beam exhibited the same poor behavior. This was despite the fact that a 65 AMeV deuteron beam had been extracted in August, 1991, after the last in a series of downward adjustments to the main coil.² One more downward adjustment of 0.4 mm was made in October 1991, and resulted in a more centered behavior of I vs. R, but the beam was not extracted. In December 1992, the beam-probe was loose and "nodding" up and down as it was moved radially so that a beam-probe signature of I vs. R on each of the three fingers could not be obtained. Such a signature could be helpful for future beam diagnostics.

It was decided to raise the main coil by 0.2 mm and this resulted in much better behavior for extraction of the 55 AMeV beams. Without further repositioning, beams of 62.5, 67.5, and 70 AMeV deuterons were successfully developed. The E1

deflector voltage for all three beams was approximately 65 KV (~6mm gap). The extraction efficiency for the 62.5 and 67.5 AMeV beams was about 20%, but for 70 AMeV, it dropped to 2%. In February 1993, the main coil was raised an additional 0.2 mm in response to poor extraction of a 50 AMeV Q/A = 0.5 beam. Although efforts at developing that beam failed, 65 AMeV deuteron and H_2^+ beams were run for 5 days in April 1993 with an initial extraction efficiency of 32% and an E1 deflector voltage of 62 kV.

ECR Ion Source

Enhancement of the ECR ion source has been tried resulting in a high-charge-state krypton spectrum which is equal to those reported by the LBL 6.4 GHz ECR³. The first stage was left off for this run. The effect of 10 hours of silane conditioning lasted approximately 1 month. Also a high-charge-state copper beam was developed using the solid-feed mechanism described in the last report. The copper was placed in a tantalum crucible with walls thinner than those used for lead and bismuth (1mm thick vs. 3.2 mm thick), in order to promote more direct heating of the copper. Table 3 lists the ECR beams available at a source voltage of 10 kV and focused through object and image slits of 12.7 mm. As before, the intensities are measured with the image slits biased positively by 120 volts in order to suppress back-scattered electrons.

Table 4 is a representative list of beams as of March 31, 1992. Several of the beam intensities were not enhanced by the buncher, but were included to show the range of the K500. Currently, the $^4He^+$ beam at 30 AMeV is the highest K (480) beam with the highest E/A. 40 AMeV $^{63}Cu^{21+}$ is the highest E beam and 70 AMeV deuterons is the highest E/A beam.

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Table I. Operational Time

	Hours	% Time
Beam on target	2282.75	39.0
Cyc. tuning, optics	2283.0	39.0
Beam development	302.25	5.2
Scheduled maintenance	185.5	3.2
Unscheduled maintenance	727.5	12.5
Idle Time	59.5	1.0
Cool down, transfer	8.0	0.1
Total	5848.5	100.0

Table II. Scheduled Beam Time

	Hours	% Time
Nuclear Physics	1715.5	30.3
Nuclear Chemistry	1939.5	34.3
Atomic Physics	869.0	15.4
Outside Collaboration	828.75	14.7
Outside Users	0	0
Beam Development	302.25	5.3
Total	5655.0	100.0

Table III. ECR Beams at 10 kV (12.7 mm slits, electron suppression).

Ion	Q	Intensity (eua)	Feeds
¹⁴ N	5	70	N ₂ + He
	6	24	
¹⁶ O	6	84	O ₂ + He
	7	11	
⁴⁰ Ar	8	31	Ar + O ₂
	9	25	
	11	12	
	12	6.5	
	13	2.0	
	14	0.5	
	16	0.006	
⁵⁸ Ni	13	7.5	Ni + O ₂
	14	6.0	
	15	4.0	
	16	2.5	
	17	1.5	
⁶³ Cu	15	5.0	
	17	2.3	
⁸⁴ Kr	18	3.4	nonisotopic Kr + O ₂ silane conditioned
	19	2.0	
	20	1.0	
	22	0.175	
¹²⁹ Xe	20	10.6	isotopic ¹²⁹ Xe + O ₂
	21	8.9	
	22	7.6	
	23	5.4	
	25	1.9	
	27	0.23	
¹⁸¹ Ta	24	5.7	Ta + O ₂
	25	3.9	
	26	2.6	
	27	1.1	
	28	0.5	
²⁰⁴ Pb			
²⁰⁶ Pb			
²⁰⁸ Pb	27	3.0 (all isotopes)	Pb + O ₂
	28	2.2	
	31	0.7	
	32	0.4	
	33	0.26	

Table IV. K500 Representative Beams
(B = buncher, C = cryopanel)

Ion	E/A (MeV/n)	I Extracted (ena)
H-H ⁺	53	5.5
H-H ⁺	65	1
D ⁺	52	5
D ⁺	55	11
D ⁺	60	25
D ⁺	65	15
D ⁺	67.5	3
D ⁺	70	5
HD ⁺	30.5	72
HD ⁺	35	15
³ He ⁺	21.5	18 ^B
⁴ He ⁺	15	600 ^B
⁴ He ⁺	30	3
⁴ He ²⁺	53	28
⁴ He ²⁺	55	40
⁴ He ²⁺	65	15
H- ⁴ He ⁺	9	3 ^B
¹⁰ B ³⁺	30	0.4
¹¹ B ⁺	2.5	6
¹² C ²⁺	5.4	1
¹² C ³⁺	20	4
¹² C ⁴⁺	30.6	2
¹² C ⁵⁺	50	3
¹⁴ N ²⁺	5.4	14
¹⁴ N ³⁺	10	1.9
¹⁴ N ⁴⁺	20	30
¹⁴ N ⁵⁺	30	200 ^B
¹⁴ N ⁵⁺	35	90 ^B
¹⁴ N ⁶⁺	40	7
¹⁴ N ⁶⁺	43.4	5.7

Ion	E/A MeV/n	I Extracted (ena)
¹⁶ O ³⁺	7.5	330 ^{B,C}
¹⁶ O ⁴⁺	20	50
¹⁶ O ⁵⁺	35	300 ^B
¹⁶ O ⁶⁺	35	180 ^B
¹⁶ O ⁷⁺	45	5
²⁰ Ne ⁴⁺	14.5	40
²⁰ Ne ⁶⁺	20	3
²⁰ Ne ⁷⁺	30	10
²⁷ Al ⁹⁺	30	140 ^B
³² S ¹¹⁺	30	6
⁴⁰ Ar ³⁺	2	14 ^B
⁴⁰ Ar ⁷⁺	8	150 ^B
⁴⁰ Ar ¹¹⁺	25	110 ^B
Ar ¹²⁺	30	65 ^B
Ar ¹²⁺	35	25 ^B
⁵⁸ Ni ¹⁷⁺	29	50 ^B
⁶³ Cu ¹³⁺	10	4.5
⁶³ Cu ¹⁵⁺	16.7	3.5
⁶³ Cu ¹⁷⁺	25	5.0
⁶³ Cu ¹⁸⁺	30	1.5
⁶³ Cu ¹⁹⁺	35	4.0 ^B
⁶³ Cu ²¹	40	0.15 ^B
⁸⁴ Kr ¹¹⁺	5	4.5
⁸⁴ Kr ¹¹⁺	6	83 ^B
⁸⁴ Kr ¹⁹⁺	15	0.5
¹²⁹ Xe ¹⁷⁺	6	59 ^{B,C}
¹²⁹ Xe ²³⁺	10	9 ^B
¹²⁹ Xe ²³⁺	12.5	9 ^B
¹⁸¹ Ta ¹⁶⁺	2	0.45 ^B
¹⁸¹ Ta ²⁴⁺	6	21 ^B

Deflector Development

R. C. Rogers, W. H. Peeler, D. P. May

Since our last report on the deflector, several modifications have been made to allow extraction of higher energy beams and improve reliability. The changes have been directed at three areas. First, the insulator design has evolved to one which is more tolerant of spark effluent contamination and takes advantage of the magnetic field to increase the voltage holding capability. Second, further efforts have been made to reduce the energy that can be transferred under sparking conditions. Finally, investigations have been made into surface treatment techniques.

Figure 1. Evolution of the deflector insulator to this time. The insulator shown is for the center of the first deflector, E1.

Figure 1 shows the evolution of the insulators from the original design, taken from early MSU designs, to the present design which employs a gap to minimize the effect of surface contamination by deflector spark or RF produced effluents. In Figure 1, the insulator "A" is essentially the MSU design. The insulator styles "B" and "C" were described in a previous report¹ and represent the first attempts to

move the metal-insulator-vacuum triple-point to a region of low electric gradient.

Figure 2. Detail of the present insulator design.

These designs were unsuccessful because they in fact created new triple-points in high gradient areas and were mechanically weak. The style "D" is a successful design as far as moving the triple-point to a low gradient point and has a stronger mechanical configuration. However, it still suffered from the effect of "plating" of a conductive track at the median plane level that led to leakage currents and eventual failure. The present design, shown as "E" in Figure 1 and in more detail in Figure 2, has a pronounced gap in the surface that interrupts the electron transit along tracks. It also forces the electron motion to be in a direction opposing the electric field on at least two portions of the surface. This design also places the triple-point in a low gradient field.

The electric field is nominally parallel to the surface of the insulator while the magnetic field of the cyclotron is directed vertically downward through the insulator and hence downward through the gap. This prevents the flow of electrons across the gap even though some tracking of the surface by spark effluents may occur. This results in zero leakage currents and in an insulator that can be easily cleaned

by gas conditioning as described elsewhere in this report.

Figure 3. Equipotential plot of new insulator from POISSON code calculations.

Figure 3 is a map of the equipotential lines in the region of the insulator as calculated by the POISSON code. The maximum gradient in the insulator gap is approximately 175 kV/cm. This calculation is confirmed by the results of ALGOR calculations which are shown in Figures 4 and 5. The highest gradient, as shown in Figure 3 and Figure 5, occurs in the insulator gap where it is adjacent to a dielectric surface rather than a metal surface. (Note that the ALGOR calculations are given in units of volts/inch rather than volts/cm.)

Figure 4. Electric field gradient map from ALGOR calculations.

This design has been successful in the cyclotron as well as the deflector test stand. The final failure mode for this insulator, in both environments, has been a punch-through of the dielectric that occurs in the region of the sharp internal corner close to the

metal end cap. This has been seen to occur on the high voltage end of the insulator. At the present time it is not known if this is due to the design itself or is a reflection of a problem in assembly that causes a void to occur in the epoxy bonding material.

Figure 5. Detail of ALGOR map in the region of the insulator gap.

This failure has occurred only after long periods of operation and at very high gradients. It may be that a small design change that adds some additional dielectric material in the region of the corner where failure occurs will suffice to prevent the punch-through.

In the previous report¹, several changes were described that were directed toward reducing the stored energy in the deflector assembly. This effort has been continued by changing the resistor in the high voltage input assembly from the previous value of 270 K Ω to 90 M Ω . The maximum instantaneous current available from the output capacitance of the power supply is thus reduced from 370 mA to 1.1 mA. This modification shows some reduction in spark damage but not as much as would be expected by the large current reduction. The damage that is now seen is probably due to the energy stored in the capacitance of the deflector itself, approximately 0.25 joules maximum at 100 kV. If this is indeed the case, then no further reduction in spark damage by stored energy reduction can be expected.

The choice of material for the deflector and its associated spark shields has some bearing on the amount of spark damage. The original deflector electrode was made of titanium and spark shields of

tungsten or stainless steel were used. It has been suggested^{2,3} that using the same materials for both gives a better tolerance for spark damage. Further, the use of anodized electrode surfaces has been suggested as a technique to reduce the amount of sparking altogether.

Several combinations of anodized electrodes and spark shields have been tried in the test stand. The first was the titanium electrode with a simple anodized surface. At the outset, the electrode was not capable of supporting voltages above 50 kV without sparking. This was caused by a rough surface texture that results from anodizing. It was found that this could be corrected by using a glow discharge in oxygen to smooth the high points on the surface. This cleaning technique is described below. After cleaning, the original anodized titanium electrode supported the full 100 kV for a short period of time but then failed to the point of being able to support only 70 kV without excessive sparking.

Anodized aluminum coatings on both the titanium electrode and an aluminum alloy electrode were also tested. In both cases a high purity aluminum (99.99%) was applied to the electrode before anodizing. The high purity aluminum is required because it was pointed out⁴ that anodizing of low purity aluminum or aluminum alloys results in a crack structure in the surface that exposes the underlying metal. The anodizing of high purity aluminum results in a small grain structure surface that does not expose the substrate metal. The anodized aluminum surface also needed to be treated with a glow discharge but was able to hold a higher voltage before treatment than the anodized titanium surface. In either case the anodized surfaces seem to hold some promise of better voltage holding capability but more testing will be required.

The suggestion^{2,3} that like metals for the electrode and spark shields are more successful has led to ordering of stainless steel electrodes for the E1 deflector. These will be micropolished and electropolished along with the stainless steel spark shields before testing in the test stand.

The glow discharge conditioning that was mentioned above is accomplished by introducing a flow of dry oxygen into the test stand at a rate to set the pressure to 40 - 100 microns. A negative d.c. voltage is applied to the electrode to initiate the discharge. The pressure is adjusted to give a voltage drop of about 750 volts across the discharge. At higher voltage levels the micro-sparking that occurs tends to concentrate in some areas and damage the surface. At the level of 750 volts or below the micro-sparking is random and seems to simply remove points on the surface. A treatment time of one to three hours was required to give the best voltage holding results.

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Quadrupole Field Mapping

J. D. Bronson, Y-W. Lui and D. H. Youngblood

Preliminary mapping of one of the beamline quadrupoles has been done as part of a program to improve beam optics generally and to design an analysis line for the MDM-2 magnetic spectrometer. A sampling of the radial and azimuthal components of the magnetic field were measured in cylindrical coordinates coaxial with the beam axis. These results were parameterized in terms compatible with the beam optics program RAYTRACE. Thus actual fringe field values can be used in all future beam line calculations.

A Group 3 commercial Hall probe was mounted in the positioning apparatus built in-house. The apparatus consisted of a bar which could be positioned with its axis of rotation located on the axis of the quadrupole. The probe mounted on a screw drive mechanism attached to this bar. The probe could be oriented to measure either the radial or the azimuthal field but not both simultaneously. In cylindrical coordinates coaxial with the quadrupole, the probe could be moved along any of the three directions of r , z , and θ .

This first design used rudimentary bearings and the resulting positioning was not as reproducible as desired. A redesign is in progress to improve the overall precision. The modified system will then be used to map several of the quadrupoles in the current beam lines. All the quadrupoles in the analysis line will be mapped. Hall probes will be permanently installed in these latter quadrupoles and the mapping will provide the needed calibration of these monitors.

Fringe fields obtained at 3 different radii are shown in Figure 1. The effective length was found to be 25.7 cm where the actual pole face length is 21.6 cm and the diameter of the opening between poles is 10.5 cm. The RAYTRACE parameterization was obtained for the 3.6 cm fringe field by a polynomial fit to $\ln(B_r/B_{mx}-1)$ as a function of Z/D where Z is the distance in cm from the effective field boundary and D is the pole gap diameter. The parameters obtained were $C01=.539$, $C02=6.980$, $C03=-10.514$, $C04=14.759$, $C05=-9.890$ and $C06=2.433$.

Figure 1. Fringe field of sample quadrupole for the radial field at a radius of 3.6 cm and for both radial and azimuthal field at 1.9 cm.

Beam Analysis System

D. H. Youngblood, J. D. Bronson, G. Mouchaty

The MDM spectrometer¹ has an inherent energy resolution $\Delta E/E$ of 1/4500. Most experiments presently planned with the MDM spectrometer, such as giant resonance studies through heavy ion excitation and mass measurements of exotic nuclei, require an energy resolution $\Delta E/E \leq 1/2500$.

No beam energy analysis system presently exists for K500 beams. The energy resolution of the beam from the K500 cyclotron was measured by inelastic ^{14}N scattering experiments at 35 MeV/nucleon on ^{92}Mo with a vertical drift chamber in the focal plane of the Enge split-pole spectrometer. With transmission of 95% of the beam from the cyclotron exit port to the target, the measured energy resolution was 700 keV. Thus, the raw beam from the cyclotron had approximately 1/700 resolution.

A beam analysis and subsequent beam transport systems were designed for use with the MDM spectrometer. The analysis system must permit matching the dispersion of the beam from the cyclotron to that of the spectrometer. For experiments where dispersion matching is not desired (or necessary), the beam transport line must provide a target spot appropriate to obtain an energy resolution of $\leq 1/2500$ while transmitting the full emittance of the K500 cyclotron within this energy window.

The facility layout including the analysis system is shown in Figure 1. An additional target station in the 88" cyclotron vault made possible by the first part of the analysis system is also shown. The analysis system consists of seven dipoles and eight quad-

Figure 1. Facility layout including analysis system.

rupoles containing an 88° counterclockwise bend with an intermediate crossover followed by an 87° clockwise bend. An additional two quadrupoles (Q9 & Q10) are required to deliver the beam to the MDM beam line. Calculated to first and second orders with TRANSPORT,² this system provides 1/2000 energy resolution through a 1.5 mm slit at the intermediate focus with restricted beam transmission, or 1/2500 energy resolution through a 3.6 mm slit at the exit slits transporting the full emittance of the cyclotron beam (5π mm mrad). The full dispersed image at the exit slit can be transported to the target with proper magnification for dispersion matching to the spectrometer. All order calculations with RAYTRACE³ using expected fringing fields showed that higher order effects do not significantly degrade the system resolution. We have no direct measurements of the emittance or dispersion for beams from the TAMU K500 cyclotron.

First order TRANSPORT calculations were done to establish element locations and strengths and to obtain optics parameters. An initial beam of 1 mm half width and 5 mrad divergence in both X & Y with no initial dispersion ($R16=0$) was assumed. We also explored the effects of larger emittance and dispersion. As the quads are 5 cm in radius we required that the beam not exceed 2.5 cm from the central ray to minimize possible aberrations. Double foci are placed between the systems and at the exit slit. The intermediate focus can be used to define the energy and the second half used for beam clean up, or the exit slit used to define the energy for maximum resolution and transmission. The beam envelope obtained from TRANSPORT is shown in Figure 2.

Second order TRANSPORT calculations were then carried out to determine the size of second order terms. The most serious term was x/θ^2 at 2.6×10^{-3} .

Figure 2. Beam envelope obtained from TRANSPORT.

A RAYTRACE calculation including fringe fields verified the x/θ^2 term. TRANSPORT was used in second order to minimize the x/θ^2 term by putting concave radii on the entrance and exit of D3. With the resulting radius, $r=112$ cm, $x/\theta^2 = -1.5 \times 10^{-10}$. This has a dramatic effect on resolution for large beam divergence. For a 10 mrad divergence the resolution would deteriorate 60% with flat predictions, but deteriorates only 5% with the radii configured. The first order parameters are shown in Table 1. Using the optimum TRANSPORT solution, 1000 random rays with maximum Δx , $\Delta\theta$, Δy , and $\Delta\phi$ of ± 1 mm and ± 5 mr with ΔE of .001% were traced through the system with RAYTRACE both for an energy corresponding to a central ray and for an energy $1/2500$ less than the central energy. The resulting distributions at the exit slits are shown in Figure 3, and excellent separation is apparent.

ANALYSIS SYSTEM - EXIT SLIT

Figure 3. Beam distribution at exit slit of analysis system for two energies separated by $1/2500$ as calculated with RAYTRACE.

To explore the effects of larger beam emittance, 1000 random rays were calculated with RAYTRACE for emittances of 8π mm mrad and 10π mm mrad in addition to the 5π mm mrad case. The percentage of the rays transmitted through the 3.6 mm exit slit of

the analysis system was 91% for 8π mm mrad and 88% for 10π mm mrad. However, for 10π mm mrad, the half width of the beam is as large as 3.5 cm in several quadrupoles. The implications of this are discussed below.

The stability of the solutions to variations in the magnetic elements was tested in several ways. Using TRANSPORT and starting with the "ideal" solution, each quadrupole was in turn changed 10% and then fixed. The remaining elements were then allowed to vary, requiring x-y foci at the intermediate and final slit positions. Similar dispersion was obtained in every case. In most cases the horizontal magnification was similar to the ideal value, however for some cases the magnification was significantly larger (up to a factor of 1.5). Various combinations of two quads were varied simultaneously with similar, but somewhat less stable results.

Table 1. Parameters of the Analysis System

<u>Exit Slit (S03)</u>	
A. <u>High Resolution Mode</u>	
X Magnification(R_{11})	-1.89
Y Magnification(R_{33})	-2.24
Dispersion(R_{16})	19.3
P/ ΔP	5000*
<u>Intermediate Image (S02)</u>	
A. <u>High Resolution Mode</u>	
X Magnification(R_{11})	1.89
Y Magnification(R_{33})	-2.24
Dispersion(R_{16})	-10.5

*Initial beam spot $\Delta x = \pm 1$ mm

Another stability test was carried out with RAYTRACE and 1,000 random rays. Each of the quads was varied in turn by $\pm 1\%$ and the calculation run. The results for quads 1 (the least sensitive) and 2 (the most sensitive) are shown in Figure 4. Several were similar to quad 1 but slightly worse (Q3, Q4, Q5, Q8) while varying quads 6 and 7 either + or -

1% gave results similar to the figure for Q2 +1%. It is clear that in most cases the spot is not affected greatly for at least 1 of the offset values and the correct setting, indicating that a 1% variation in a quadrupole, even if uncompensated by other quads, will not significantly degrade resolution. It is clear that Q2 is the most sensitive. Subsequently, calculations were carried out with 1 quad off 1% and then varying individually each other quad by $\pm 1\%$. Again for each quad either the +1% or the -1% value resulted in resolution similar to the optimum solution.

ANALYSIS SYSTEM - QUAD VARIATION

Figure 4. RAYTRACE predictions for the beam distribution with Q1 and Q2 offset by $\pm 1\%$.

In the simplest form, the dispersion of the beam at the entrance to the analysis system (times the

magnification of the analysis system) adds to the dispersion of the analysis system, producing greater or less overall dispersion depending on their relative signs. In order to maintain dispersion matching, the magnification of the transfer line between the analysis system and the spectrometer must be adjusted. The quad triplet performs this function. However, when the net dispersion is reduced, the overall resolution will be reduced (whether dispersion matched or not!). The resolution can be restored (in the dispersion matched case) by reducing the slit opening (x) at the entrance of the analysis system.

Four cases representing extremes of beam dispersion from the K500 were studied with TRANSPORT. No variations from the solution with K500 dispersion = 0 were allowed except for the values of the fields in the elements of the quad triplet preceding the spectrometer. A focus was required on target and that the solution must provide dispersion matching in the focal plane. Extreme cases where the entire measured beam energy spread was correlated in position with both possible signs and where the entire spread was correlated in angle with both possible signs were considered. For the object size and divergence we assumed at the entrance to the analysis system, these corresponded to initial values as follows: (1) R16 = 1.9cm/%, (2) R16 = -1.9 cm/%, (3) R26 = 48 mrad/% and (4) R26 = -48 mrad/%. For cases 1 & 2, R26 was set to 0 and for cases 3 & 4, R16 was set to 0. In each case a solution was found with at most minor variations in the triplet fields and the solutions were well behaved. The beam remained small (≤ 2.5 cm half width) and nearly upright ellipses were obtained on target. The magnification on target varied from .8 to 1.1 for cases 1 & 2 (it was .97 for R16 initial = R26 initial = 0) due to changes in overall dispersion. The decrease in dispersion for case 2 was 15%. The desired resolution of 2500 can be obtained by closing the input slits of the analysis system by 15%, reducing the transmitted beam accordingly.

If the beam could be allowed to exceed 2.5 cm half width in the quadrupoles, considerably higher resolving power can be obtained with the system. By

moving Q6 and Q7 50 cm away from Q5 and Q8, respectively, and not using Q2, the resolving power of the system can be raised to $P/\Delta P$ of 8400 while retaining the stability to tuning. This would be well matched to the maximum capability of the MDM. In this configuration, the half width of beam is nearly 4 cm in one quadrupole and is over 3 cm in 4 of the quadrupoles. However, when the half width of the beam exceeds about 2.5 cm in our quadrupoles, a rotation of the beam occurs (the image of an X-Y slit pair is rotated!) which increases with increasing beam size. This would seriously degrade resolution, so the system is configured to limit the half width of the beam below 2.5 cm. Beam rotation has not been explored systematically. Field maps of the quadrupoles planned as part of this project should provide better information.

Figure 5. Beam analysis system including position of viewer, slits, and Faraday Cup. Quadrupoles QA and QB are necessary only for radioactive beam solution.

Several beam diagnostic elements will be installed to verify proper beam placement and to allow adjusting optical elements to obtain the desired solution. These are shown in Figure 5. At positions S01, S02 and S03 complete systems of 4 jaw slits, viewers and Faraday cups will be installed. With these, foci can be established at these locations and small objects created with the slits for subsequent focusing. To insure that the beam is entering and exiting each dipole properly, viewers will be located appropriately before and after each dipole. Since Q2

does not focus the beam but only serves to reduce the X extent entering Q3, a viewer just before Q3 will be used to monitor beam size at this point. A viewer at the 0° exit of D1 will, in conjunction with the slits at S01, establish both the path of the beam entering the analysis system and the initial divergence of the beam.

Studies of beam transmission to the MDM spectrometer from the analysis system have been carried out with TRANSPORT. A quadrupole triplet, used with the Enge spectrometer beam line to allow variable magnification for dispersion matching will be used in this line for the same purpose. The configuration of the beam line to the MDM is shown in Figure 1. Satisfactory TRANSPORT solutions were found to carry the beam to the MDM target both to a beam spot 2 mm wide by 2 mm high with the exit slits on the analysis system set for 1/2500 energy resolution (3.6 mm slit at the exit of the analysis system) and to a spot on target appropriate for dispersion matching with transmission of essentially full beam from the K500 cyclotron. The TRANSPORT solutions for both are shown in Figure 6.

The beam analysis system consists of 8 quadrupoles and 7 dipoles. The quadrupoles, have 5 cm radii, a 25 cm effective length and an 8 kG maximum field. The parameters of the dipole magnets are summarized in Table 2. All have pole tips approximating Rogowski shape at the exit and entrance. The dipole D6 was the prototype magnet for the HISTRAP atomic cooler ring at Oak Ridge and its field was mapped there. It was designed for a 45° bend, but at 16 kG (maximum design field) a K500 beam will bend 37° . With a 37° bend, the good field width is ± 5 cm. D2 was built by Bruecker to specifications requiring that the field be flat within .01% over an 8 cm width, and this was verified during field mapping at Bruecker. Maps of the fringing field of D2 done recently show a stable effective field boundary from 8 to 14 kG. The other existing dipoles have not yet been field mapped.

(a)

(b)

Figure 6. Beam envelope from TRANSPORT onto target at the MDM spectrometer. (a) $\delta p/p = 0$, at target $R_{11} = 1$, $R_{33} = 1$; (b) $\delta p/p = 1/1400$ from cyclotron, at focal plane $R_{16} = v$.

The flat field regions of D3, D4, D5 and D7 have been modeled with POISSON⁴ and found to vary less than .02% over ± 10 cm. The field predicted by POISSON is plotted in Figure 8. A second order term (in RAYTRACE notation BET1) of 0.284 is apparent. RAYTRACE calculations showed this had no effect on the optics, even when the central ray of the beam was displaced as far as 6 cm from the center of the magnet.

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Figure 7. Magnetic field near central ray calculated with POISSON for window frame dipoles. Line is quadratic fit.

Table 2. Dipole Parameters

	Construction	Bend Angle K=500	Field K=500 (kg)	Flat Field Width (cm)	Effective Length (cm)	Pole Gap (cm)	Pole Face		Source
							Entrance	Exit	
D1	H	18°	10.15		101	6.4	Flat, $\perp$	Circular R-500 m	Scanditronix 1966
D2	H	30°	14.10	6 ^b	121 ^a	4.4	Flat, $\perp$		Bruecker 1987
D3	Window Frame	20°	14.35	8 ^b	79.5 ^c	7.1	Flat, 10°	Convex 112 cm, 10°	TAMU 1991
D4	Window Frame	20°	14.35	8 ^b	79.5 ^c	7.1	Flat, 10°		TAMU 1991
D5 & D7	Window Frame	25°	15.00	8 ^b	95 ^c	7.1	Flat, 12.5°		To be constructed
D6	C	37°	16.00	$\pm 5^a$	132	7.0	Flat, 18.5°		ORNL- HISTRAP

- a) Measured
- b) Calculated with Poisson
- c) Design Goal
- d) Specification

Single Event Effect Facility

R. C. Rogers, D. P. May, R. A. Gutierrez, and P. Smelser

The Cyclotron Institute has entered into an agreement with McDonnell-Douglas Aerospace Corporation to provide irradiation facilities for the measurement and characterization of Single Event Effects (SEE) in VLSI components. The initial phases of this program will be to support the Space Station Freedom project. A longer term collaboration with the Electrical Engineering Department at Prairie View A&M University, Prairie View, Texas, will support a qualification program for a wider range of space-borne VLSI applications.

Figure 1. Modified Ortec chamber showing positioning mechanism.

Figure 2. Modified Ortec chamber shown with upper and lower extensions in place.

The irradiation chamber will be constructed from an existing Ortec scattering chamber. The chamber will be modified by the addition of upper and lower extensions to increase the clear inside space. New pumping equipment will be added as well as an X-Z micropositioning device. The supplier of the X-Z

positioner, Design Components, Inc., is also supplying hardware interfaces and control software. The chamber already has a rotational mechanism so an X-Z- θ positioning capability, that is supported by the software, will be available. Drawings of the modified chamber with the positioning mechanism in place are shown in Figures 1 and 2. The facility will be located on a spur beamline that branches off the beam analysis system as shown in Figure 3.

Figure 3. Location of SEE chamber in 88" cyclotron vault.

To insure proper location of the beam spot on the component under test a technique of low intensity beam imaging using a CCD camera and a target coated with Zinc-Cadmium Sulfide Fluorescent Indicator is being developed. The system uses a camera¹ and software package² originally developed for use in astronomy. This is almost ideal for analysis of beam shape and cross-section profile measurement because of the similar requirements of astronomical imaging. An image obtained in preliminary tests of the system at beam intensities of less than 10^6 particles/sec. is shown in Figure 4. Tests with a similar system already in use at the laboratory has demonstrated capabilities of imaging beam intensities as low as a few thousand particles/sec. The capability of the software to superimpose the beam image on a previously stored target image makes it possible to see the exact physical relationship between the particle beam and the device under test.

Figure 4. Image of a 100 epA beam of $^{129}\text{Xe } 21+$ at 8 MeV/A.

Figure 6. Superposition of beam image on viewer.

Figure 5. Image of fluorescent viewer target.

Figure 7. Cross-section profiles of beam image.

Figure 5 is the image of the fluorescent viewer and Figure 6 shows the superposition of the beam image on the image of the viewer. Figure 7 is a plot of the horizontal and vertical cross-section data extracted from the beam image.

The initial use of the facility will be a comparative study of data obtained from a similar facility at Brookhaven National Laboratories. These tests are planned for November, 1993.

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Computing at the Cyclotron Institute

K. Hagel and H. Dejbakhsh

The second year of a three year upgrade to the cyclotron computer facilities was implemented in 1992. The first year of the upgrade, as reported last year,¹ was basically used to alleviate the worst crunch on a lab wide basis. That being accomplished, most computers purchased in 1992 were for the individual use of various groups.

A set of 5 VaxStation 4000/model 90's were purchased. One of these, named CYCOMP was put into our cyclotron wide cluster known as the COMP cluster. This machine was meant to be used as a compute box for large batch jobs. It has also replaced COLOR as the boot server for the cyclotron cluster. This machine now serves our user disks, as well as 3 Gigabytes of scratch space and one 8mm tape drive used primarily for backups. The other four machines were distributed to the various groups who requested them and are being used in ways that these groups deem fit. As it turns out, they are used for a combination of tape scanning and batch computations that these groups perform. Each of these machines is equipped with a 1 Gigabyte disk and most of them are equipped with an 8mm tape drive.

In addition to these machines, we accepted delivery of the first ALPHA AXP system on the Texas A&M campus. This is the new 64 bit RISC machine that DEC has recently released. It runs the new OPEN VMS AXP which appears to the general user to be exactly the same as VAX-VMS. We have ported several of our calculations to this machine with little or no problem. The advertised 108 SpecMarks enable us to do calculations that were previously out of the range of our computing capabilities. It is also equipped with 2 Giga bytes of scratch space.

Several printers have also been purchased. Most notable among these is a PHASER III PXi from Tektronix. This PostScript printer has the capability of printing color on regular text paper, and can make

transparencies directly. It has the convenient feature of using solid ink sticks, so ink spills are eliminated. This printer is connected directly to the network and is therefore accessible to all systems on the network including the VMS systems, UNIX systems and several DOS systems which have a network card in the PC's. Other printers that have been purchased include two HP4M printers that are available on a lab wide basis, and one HP LaserJet III connected to the acquisition system for printing online plots. The two HP4M printers are also placed directly on the network. The other HP printers are operated through a print server using the parallel output to enhance print job turnaround.

During the first phase of the computer upgrade we isolated the Cyclotron network traffic from the rest of the campus by installing a two port Ethernet CISCO Bridge/Router (see Ref. 1). As our computer grows rapidly so does our local network traffic. Due to the increased network activity during the year, we decided to upgrade our Bridge/Router unit. The Cyclotron LAN layout before the upgrade is shown in Figure 1. The network upgrade plan is as follows:

1. We will eliminate the thickwire Ethernet by converting from thickwire to thinwire Ethernet. At present we have completely eliminated the need for a DELNI (see Fig. 1).
2. We have purchased a new (faster throughput) bus controller in addition to a four ports Ethernet controller for the Cyclotron Router. A thick to thinwire transceiver for each Ethernet port will allow us to utilize each port as a single LAN. Therefore we have the potential of setting up to four additional LANs at the Cyclotron. We are planning to eliminate the use of repeater in the near future as we move more nodes to the other LANS. Part of this plan has been already implemented, but as you have already noticed, the full implementation of the for LANS requires re-wiring of the network links. For the near

future our LANS will set up using three LANS. One will be for the VMS systems, the other for the ULTRIX systems and the third for PC's. Further network re-configuration will take place as the need arises. A sketch of the Cyclotron network system in near future is presented in Fig. 2.

We have also acquired a shareware electronic mail exchange utility in preparation for DECnet phase 5 installation. This utility will replace our GMAIL utility which is used extensively by our users.

During the second year of the upgrade we have purchased a few PC 486 with 8 Mbytes of memory and 200 to 350 MB of hard disk. These systems have super VGA controllers and color monitors for individuals.

There has been no change to the data acquisition system since our last report,¹ except for replacement of some failing Exabyte tape drives and addition of printers to some of the data acquisition systems in anticipation of a major data acquisition upgrade. The Exabytes tape drives and printer can and will be ported to any new system we acquire.

At present we are in the third year of our three year computer upgrade. This year we will mainly concentrate on upgrading the data acquisition system. We will evaluate a few available systems in other National Labs and Institutes to decide which one will better serve our diverse needs and be within our budget.

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Figure 2.

Commissioning of the Proton Spectrometer Facility

A.C. Betker, C.A. Gagliardi, H. M. Xu and A. F. Zaruba

During this past year, we performed our first measurements with the complete proton spectrometer (PSP) facility. Figure 1 shows the layout of the entire system. It consists of a dipole magnet, 2 5-layer drift chambers for position measurements, and 2 scintillator hodoscopes for energy loss, timing, and trigger information. The full facility is described elsewhere¹. The system is designed to permit a systematic study of $T_{>}$ Gamow-Teller matrix elements across the periodic table with an energy resolution of 500 keV FWHM, significantly better than is presently available. The reactions for these measurements are both $(d, {}^2\text{He})$ and (n, p) scattering.

Figure 1. General layout of the proton Spectrometer. The deuteron beam enters from the right.

The tests described in the rest of this report were performed with a 111 MeV deuteron beam from the K500, incident on a 11 mg/cm² thick C target. This beam is not optimal for the PSP in ${}^2\text{He}$ mode because the energy resolution varies inversely with the beam energy. The range of accepted excitation energies is also a function of the ${}^2\text{He}$ energy, due to the kinematics involved. For those parameters where beam energy is a hindrance, however, this lower beam energy provides worst case performance data. The magnet was at a scattering angle of 10°, with an angular acceptance of $\pm 7^\circ$. The Q value for the ${}^{12}\text{C}(d, {}^2\text{He}){}^{12}\text{B}$ reaction is -14.81 MeV, which, along with kinematics, leads to decay protons of about 47.6 ± 10.0 MeV for the ground state. The magnetic field was set at 9.081 kG to put protons of 50.06 MeV on the central ray. At this field, protons from 32 to 90 MeV reach the detectors, as well as deuterons from 16 to 45 MeV. Aluminum absorbers

were used between the scintillator hodoscopes to eliminate non-protons from the singles trigger.

The singles (SS) trigger requires that there be at least one hit in each scintillator hodoscope. Given the thickness of the Al absorber, this virtually assures a proton trigger. This configuration allows us to calibrate the entire detector system, and then to evaluate its performance. Particle tracks are found through the detector system. Once these trajectories are known, magnet matrix elements relate these outgoing trajectories to the particle trajectories leaving the target and their energies. This allows us to reconstruct the reactants at the target.

The track selection is done on a χ^2 minimization basis. Events with 10 points that do not meet the χ^2 criterion are permitted to eliminate one point. Those with 9 points that fail the χ^2 cut are allowed to eliminate one point from the drift chamber (DC) that has no missing hits.

Figure 2. X coordinate of all tracks at the exit of the vacuum chamber.

First the scintillator timing is calibrated by finding the relative time jitter for every scintillator trigger pair. Then the drift chambers are calibrated to provide the correct displacement for each measured time. This process is iterative. A first approximation can be made with the assumption that the detectors are uniformly illuminated. This initial calibration, however, is only approximate. The detector region is not uniformly illuminated, as there are many more protons from deuteron break-up at the high ρ end of the magnet, and there are window supports that

shadow some regions of the detector. This shadowing is shown in the spectrum of the fitted track x coordinates at the exit of the vacuum chamber, Fig. 2. A residual error for a track can be obtained by eliminating one layer at a time from the best track, re-fitting the rest of the points, and then subtracting the measured value from this fitted value. The calibration can be corrected by computing this residual error in a layer and correcting the initial displacement vs. time calibration for the error. This process converges in 4 iterations for this data set.

Figure 3. The residual error as a function of position, after the final wire time offset corrections.

Figure 3 shows the residual error for a pair of layers, as a function of position across the detector. The residual errors for a layer can be fit with a double Gaussian. The taller Gaussian represents the intrinsic resolution of the layer. The shorter, broader Gaussian includes those tracks that scattered in a window support or wire or had real hits obscured by electronic noise, but still passed the chi-squared cut. One such fit is shown in Fig. 4. The width of the residual error is related to the FWHM resolution of a layer by geometric factors that account for the layer to layer distances. A complete list resolutions is given in Table I. All of the resolutions are comparable to or better than those required for the ultimate desired system energy resolution of less than 500 keV.

Our fit results permit us to obtain detailed efficiency information for the various detector layers. This is done by two different methods. The first method is a simple counting method. All tracks that have 10 layers hit in interior cells are compared to those that have 9 layers hit in interior cells. So long as a track is not in an edge cell anywhere, there should be one hit in every layer. The second method does not exclude edges and uses tracking instead to

Table I: Drift chamber position resolutions and efficiencies.

Layer	Resolution (FWHM, μm)	Efficiency (%) Counting	Efficiency (%) Tracking
X1	238	97.7	95.8
X1'	219	97.8	95.5
U	235	98.9	97.1
Y1	233	99.8	99.1
Y1'	231	99.9	99.1
X2	218	98.7	97.2
X2'	196	98.1	96.9
V	229	98.8	96.7
Y2	226	98.2	97.5
Y2'	238	98.4	97.5

compare successful 10 point tracks to those with missing or dropped hits in 9 point tracks. The second method results in inefficiencies about twice as large as simple counting. Layer by layer efficiencies are also given in Table I.

Figure 4. Typical double Gaussian fit to residual error histogram. Dashed curve (taller) measures intrinsic resolution. Dotted curve (broader) is multiple scattering Gaussian. Smooth curve is sum of these two.

Overall tracking efficiency was 61% 10 point fits, 24% 9 point fits, and 6% 8 point fits. Of the full data set, 87% of the events had enough hits for possible 10 point fits.

Converting the observed track coordinates into the physical quantities of interest - proton energies and emission angles- requires an understanding of the PSP magnetic field. Our field map shows that the uniformity of the field over the active region of the spectrometer is excellent - better than 0.03% at 9 kG and better than 0.1% at 16.5 kG, compared to the

design specification of $<0.4\%$ non-uniformity at high fields. The effective field boundaries are displaced approximately 2 cm from the locations predicted by POISSON², thus making the effective length of the magnet somewhat longer than anticipated. This shifts the momentum for perfect point-to-parallel optics to about 2% below that of the central ray. We have fed the preliminary analysis of our field map into RAYTRACE³ to obtain the matrix elements of the PSP magnet. We then apply them to our data sets to gain information about the overall system acceptance and magnet performance. The outgoing tracks can be related to the ingoing energy and scattering angle by utilizing a piecewise linear fit. Once the energy of each proton is available, the system acceptance can be examined. Figure 5 shows the ingoing θ as a function of energy, and as such provides the best information on the system acceptance. The upper and lower cut-offs are the angular limitations, imposed by the entrance slits, while the curved cut-offs on the sides are the edges of the detector system at the back of the magnet. The effect of the window support bars can be clearly seen. It should be noted that we currently find a 1.3% discrepancy in the momentum scale between our field map and our observed particle trajectories. We are investigating this at present.

Figure 5. Scattering angle about 10° vs energy. The overall acceptance of the system is limited by slits in the θ direction and by the edges of the detector system along the energy direction.

The SS data set is a useful diagnostic and calibration tool, but the primary physics trigger is SDNA. This requires at least two non-adjacent particles in one of our scintillator hodoscopes and at least one in the other. The trigger is however only the first step in identifying the ^2He proton pairs. One

of the scintillator hits may be a deuteron or neutron, or the particles may be a random coincidence of two protons, rather than a diproton break-up pair. Steps need to be taken to eliminate these other types of events. Particles heavier than deuterons are bent too far in the magnetic field to reach the detectors, so they do not further complicate the analysis. First the non-proton events are separated out, and then the proton-proton events are examined more carefully in an attempt to identify the relative numbers of good diproton pairs to random proton coincidences.

Figure 6. Relative times of non-adjacent double hits in X and Y scintillator arrays, as seen at trigger time. Times are raw times in X and raw mean times in Y, before any time offset corrections have been made.

As described above, we inserted an Al absorber between the two scintillator layers to eliminate as many non-protons from the SS trigger as possible. A neutron or deuteron in random coincidence with an SS trigger will, however, produce an SDNA trigger. To be in time coincidence, all of the necessary scintillator signals must arrive at the trigger board within 60 nsec. This permits particles from neighboring RF cycles to be part of a trigger event, but particles from two RF cycles away cannot. At the energy range of this experiment, protons from real ^2He decays arrive within about 10 nsec of each other, after the trigger time corrections have been made. Since the magnet selects particles by momentum, the deuterons in the acceptance range are traveling at about half the velocity of the protons. This leads to a time difference between the particles in a proton-deuteron event of about 15-20 nsec. The relative times for non-adjacent X scintillator doubles and non-adjacent Y scintillator doubles as they are seen at trigger time are shown in Fig 6. An energy loss cut

in the X hodoscope eliminates most of the deuterons. Neutrons do not interact with the drift chambers, so proton-neutron events do not have enough hits for 2 tracks. This effectively eliminates the proton-neutron events. Between them, these two constraints eliminate 46% of the data. At this stage, further data reduction must be done by detailed tracking.

The tracking proceeds very much like it did for the singles case. In the remaining 54% of the data set, two tracks are found 37.5% of the time, one track is found 11.5% of the time, and in 5% of cases, no tracks are found. The percentages are averages over all data sets. The significantly poorer tracking efficiency here, compared to the singles data, is the result of two effects: (1) the two particle tracks sometimes interfere with one another, and (2) the deuterons left in the data set have a significantly poorer tracking efficiency.

The relative times of fitted tracks are shown in Fig. 7. The times are now corrected for transit time and trigger jitter, which was not possible before tracking, so the X distribution is now more symmetric. The spectra are now very clearly separated into two-proton events from the same RF cycle, and two-proton events from neighboring RF cycles. The final S:N's are 6.9:1 in X and 7.9:1 in Y. Examination of the events out-of-time by about 42 nsec provides useful information about the expected numbers and energies of random protons within the same cycle.

Figure 7. Relative times of the double hits in the X and Y scintillator arrays, after tracking. The times in this figure are now the corrected times in X and corrected mean times in Y.

The θ of each track is related to its energy. Comparing the $\tan(\theta)$'s of the two tracks gives the

distributions shown in Fig. 8. Converting the measured proton trajectories into energies and incident angles yields the results in Fig. 9. Note that the bands in the picture, which were curved in Fig. 8, are now straight, as well as being narrower. A third band is also now visible. This straightening is the result of the corrections for the higher-order aberrations. A total ^2He energy can now be reconstructed by adding the proton energies. Further information is also available concerning the trajectory and internal energy of the ^2He . The ingoing θ of the ^2He is simply the scattering angle, relative to the magnet location of 10° .

Figure 8. Relative $\tan(\theta)$'s for the two protons. Note the strong correlation for the protons.

The reconstruction of the ^2He permits the addition of fiducial cuts that provide a relatively uniform acceptance efficiency. The internal diproton energy distribution is shown in Fig. 10. Allowing only ^2He 's within $\pm 4^\circ$ in θ , within $\pm 1^\circ$ in ϕ , and with internal energy of less than 1 MeV improves the energy resolution further. The final energy spectra are shown in Fig. 11. Here the ^{12}B ground state, the first excited state at 953 keV, another at 2.62 MeV, a group of states at 4.5 MeV, and an additional group at 7.8 MeV are visible. The ground state resolution is about 720 keV, FWHM. Other states are either poorly populated and/or broader due to the density of states and their intrinsic widths. Predictions of the resolution as a function of energy are shown in Table II. The present data was taken with a beam spot that was wider than optimal for $(d, ^2\text{He})$, leading to the beam spot contribution which is not generally present. The detector resolution is constant at all energies. The multiple scattering in the first drift

chamber varies inversely with energy, leading to an improvement in the resolution at higher energies. The resolution estimate for the present data set is 710 keV, very close to that actually measured. For proton energies of 80 MeV, this improves to 490 keV, which is comparable to the design energy resolution of less than or equal to 500 keV. The accepted energy range increases at higher energy as well, so higher excitation energies will be seen.

Figure 9. Relative proton energies. The broad bands are the ^{12}B excitation spectrum.

Figure 10. ^2He internal energy. The data resembles the theoretical distribution as expected.

The initial phase of the Proton Spectrometer project - the design, construction, and testing of the apparatus - is now complete. The magnet and associated detector performance is very close to the design specifications. This equipment will now be used to help address the nuclear physics questions it was built to address. As this is being written, we

have just completed a run in which $^1\text{H}(d,^2\text{He})n$ and $^{12}\text{C}(d,^2\text{He})^{12}\text{B}$ cross sections and angular distributions were measured at a beam energy of 130 MeV and scattering angles of 0-15°. The analysis is just beginning. We will follow up with studies of several more light nuclei, in order to investigate the details of the $(d,^2\text{He})$ reaction mechanism in this energy range, and then move on to measurements of isovector spin-flip strength in medium mass nuclei that are important for double β decay, The Gamow-Teller sum rule, and supernova evolution.

Figure 11. ^2He energy w/fiducial cuts. Scattering angle is $10 \pm 4^\circ$, $\phi \pm 1^\circ$, and internal energy < 1 MeV. Ground state resolution is 720 keV. Other ^{12}B states are seen at .953, 2.6, 4.5, & 7.8 MeV.

Table II: Expected system energy resolution. All numbers are FWHM, and are for the 2 protons combined. The observed resolution at 48 MeV is 720 keV.

Proton Energy (MeV)	Beam Spot (mr)	Detector Resolution (mr)	Multiple Scattering (mr)	Total (mr)	^2He Energy Resolution (keV)
48	4.8	1	5.1	7.1	710
60	1.3	1	4.1	4.4	490
80	1.3	1	3.1	3.5	490

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Construction and Initial Operation of MARS

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The major construction for MARS was completed by early fall of this past year. The only remaining component of the system that is not yet installed is the general purpose scattering chamber. Consequently, initial operation has been carried out with the simple 0° chamber. Below, we discuss the work that was carried out during the final phase of construction and then we discuss our experience with the initial operation of the system. A layout of MARS as it is now configured is shown in Fig. 1.

Magnetic Systems

During the spring of '92, the three dipole magnets were assembled without their vacuum chambers and field maps were made of the central regions and the entrance and exit field boundaries. The field maps closely reproduced the results that we had obtained from modeling the magnets with POISSON. The vacuum chambers for the three dipoles arrived by early summer. The chambers for D1 and D3 were installed by mid summer and leak checked. The chamber for D2 did not meet our specifications and would not fit into the dipole. It was returned to the contractor for modifications. A temporary chamber was built by our machine shop which did not use the pole tips of D2 as part of the vacuum system. Preliminary tests of the optics of the system were carried out with this temporary chamber in place. The final chamber arrived here just before Christmas, and it was installed in January of this year. The dipoles D1 and D2 have NMR read-outs to set the fields while D3 uses a precision Hall probe. Both the NMR and Hall probes are read out with the K500 computer control system for remote tuning and monitoring.

A careful field map of the exit of one of the five large quadrupoles was completed before last summer from which we found that the effective length of the quads was 70 cm. Quadrupoles Q1 - Q3 were in

place by late last spring and utilities connections were already completed. Q4 and Q5 were mounted on the movable table at the exit of D3 by late summer and utilities were connected by the end of September. All five quadrupoles have been instrumented with Hall probes. These probes, which sit outside the vacuum system on a pole tip, have been calibrated against a probe that was placed inside the vacuum can next to the same pole tip.

The sextupole S1 was installed by early summer and S2 was installed on the movable arm before the end of September. Utilities to both sextupoles were connected just after they were installed. The beam line swinger magnet was completed by early summer and installed on the movable table in front of the scattering chamber by July '92.

Velocity Filter

During the late summer and early fall of '92, we conditioned the plates on the velocity filter up to 350 kV in hard vacuum with no magnetic field. We found that with the magnetic field on, the plates would hold substantially less voltage and the system did not seem to condition itself in this mode. Following a test run in December, we opened the velocity filter and did a careful inspection to determine if we could find the source of the problems. We modified some hemispheres which are located on the bottom of the negative plate strongback which appeared to be a source of sparking. These hemispheres are made of Al and the surfaces were too rough for the voltages which we were trying to hold. Unfortunately the modifications that we made reduced the maximum voltage that we have been able to hold to about 250 kV. We recently have built stainless steel replacements for these hemispheres which we plan to install by early summer '93. Also during late March of '93 we installed heater elements inside the vacuum system so that we can thoroughly

Figure 1. Present layout of MARS

Figure 2. Position vs. energy spectra obtained at the focal plane of MARS. The top figure has a 0.6% momentum acceptance and the bottom one has a 1.2% acceptance.

outgas the ground shield. With the heaters installed, the plates were able to hold the same voltage (about 250 kV) with the magnetic field on as with it off.

We have encountered several problems with the HV power supply this year. The system had some modes of operation that looked like HV breakdown but did not appear to be coming from inside the velocity filter or in the HV decks. Problems would appear and then disappear without any apparent reason. During a recent test run, we discovered that the system periodically would make discrete jumps in the output voltage and that there was noise on the negative plate HV that resulted in a broadening of the peaks at the focal plane. Following that test run, we have begun to thoroughly debug the control system and the two inverters. A number of problems have been uncovered and fixed during this process. We hope to complete the checks by early May.

Vacuum and Support Systems

The vacuum components were all completed and installed by September '93. The movable arm at the end of D3 was installed and tested by late last summer. The FC chamber located between D1 and Q3 was instrumented with movable Faraday cups along the sides. Also fixed cups were placed at the ends of the chamber and a slit system was installed just before Q3. The slit system is used both to define the momentum acceptance of the achromat and to stop the beam when the beam momentum is close to the recoil momentum. A provision has been made in the FC chamber to install a "finger" FC which will intercept the beam particles when they are mixed in momentum with the recoil ions. Also the vacuum control system was completed before the end of '92 and was installed just after the first of this year.

Initial Tests

During the past few months, we have carried out a number of test runs with MARS using ^{58}Ni beams at 29 MeV/u. The goals of these tests have been: (1) find the 0° line into the target chamber; (2) determine if the optics work as predicted; (3) "calibrate" the magnets and the velocity filter; (4) determine our

ability to reject the primary beam at 0° for inverse kinematics reactions; (5) determine if the environment at the scattering chamber is suitable to carry out particle-gamma coincident measurements; (6) measure a mass spectrum. These goals have now been completed and we are beginning to use the device to carry out our first physics measurements.

The bend angle into MARS is set by two bending magnets that make up the dipoles on the beam swinger. A viewer is located in front of the second swinger magnet which allows us to put the beam from the first bending magnet on the center line of the second. In order to determine the 0° line, we used a transit to locate a target in the beam pipe approximately halfway between Q1 and Q2. The beam was then centered at the target location and the bending magnets were adjusted until the beam on the second viewer was also centered. With the beam in this location, we observed no steering in Q1 or Q2.

In order to check the beam optics and calibrate the magnets, we have used phosphor viewers that were located along the beam line with transits in the FC chamber just after D1, just before Q3, and at the focal plane after Q5. The direct beam is then viewed with a television camera. The two viewers in the FC chamber allow us to set the magnetic field in D1 so that the beam is traveling along the optical axis in the section of the momentum achromat between D1 and D2. The viewer before Q3 is useful to check the settings on Q1 and Q2. By making relatively small changes in these quadrupole fields, it is possible to produce a double focus at this location. Dipole D2 can be set using the last viewer with the velocity filter, D3, Q4 and Q5 turned off and the bend angle after D3 set to 0° . However, the image at the viewer is rather large. With D2 set, Q4 and Q5 do not steer the beam but focus it as expected. The velocity filter E and E fields are calibrated against each other by keeping the beam centered at the focal plane while turning up the two fields. We have used both a phosphor viewer and a focal plane detector to check the E and B fields. By detuning a solenoid in the ECR source transfer line to lower the beam current, we can view the beam through MARS on a focal

plane detector. The detector that we have used for these studies is a 10 cm single-wire gas proportional counter backed by a 1cm x 5cm x 500 μ m Si solid state counter.

As noted above, these studies have been carried out with a ^{58}Ni beam at 29 AMeV. We chose this beam since we plan to carry out several experiments using ^{57}Cu recoils produced by the inverse kinematics reaction $p(^{58}\text{Ni}, ^{57}\text{Cu}) 2n$. The Q-value for the reaction leading to ^{57}Cu is -21.5 MeV and the threshold energy for the reaction is about 21.7 AMeV. At this energy, most of the beam and recoil ions are fully stripped after they leave a target that is at least 1 mg/cm ^{2} thick. Thus the ^{57}Cu recoils have a p/q that is about 7% smaller than the beam. With the fields setup to observe the ^{57}Cu recoils, the primary beam stops on a Faraday cup near the back of the FC chamber before the entrance to Q3. We found two places where beam particles could scatter and be transmitted to the focal plane with the ^{57}Cu settings. One source of scattering was the movable FC on the high ρ side of the FC chamber. By changing the shape of this cup and moving it very close to the back slit, we were able to eliminate the scattering from it. The other source of scattering is the NMR probe that is located inside of D1. We have modified the probe mount with a bellows that allows us to pull the probe out of the way after the magnetic field is set. Of course we cannot monitor the magnetic field in D1 with the probe out but we use a common power supply for D1 and D2. Thus by monitoring D2, we can determine how stable that supply is. D1 also uses a trim coil supply so that we can adjust the D1 and D2 fields independently over a small range. The current in the trim supply must change by a significant amount before it causes an adverse effect on the magnetic field in D1.

Figure 2 shows two position vs. energy (Si detector) spectra that we obtained from a 7 mg/cm ^{2} CH $_2$ target with the ^{57}Cu settings. The momentum acceptance slits were set at about .6% and 1.2% full width for the two spectra. The change in acceptance is clearly shown by the change in the energy spread for the different groups in the figure. By opening the slits further, we observed a group from the production of ^{58}Cu that occurred at the same position as the ^{56}Ni group. From Fig. 2, it is clear that ^{57}Cu is nicely separated from other recoil ions in this reaction. The data were taken with a small dispersion, approximately 3 mm/% Δ m/m, since we were encountering problems with the HV power supply on the velocity filter. During the run where the data in Fig. 2 were collected, we checked the rates in a Ge detector located at the target chamber and collected a small amount of particle-gamma coincidence data. We found that the Ge detector rate scaled very closely with the target thickness, and thus background due to beam optics and the beam stop at the FC chamber was minimal.

We have nearly completed the construction of a cryogenic gas target that we plan to use in place of the CH $_2$ solid target. The gas cell will allow us to substantially increase the beam current and, hence, increase the yield of recoils like ^{57}Cu so that we can study their decay or carry out secondary reaction measurements. The gas cell will be tested in the MARS target chamber in May once again with the ^{58}Ni beam. We will monitor the ^{57}Cu yield as a function of gas pressure and thereby determine the cross section for the reaction and the expected yield of ^{57}Cu for beta decay measurements that we plan to carry out beginning in the summer of '93.

Beam Rate Estimates for MARS

J. A. Winger

The MARS system at the Cyclotron Institute provides a useful means for the production and isolation of radioactive ion beams.^{1,2} A wide range of beams may be produced using this system, however determining the rates of each beam directly would be a formidable task. Instead, it would be useful to obtain reasonable estimates of the beam rates using our knowledge of the various physical processes involved. These estimates could then be used in the planning of experiments prior to actual beam rate measurements being made. In order to achieve this goal, we plan to adapt the INTENSITY program³ which has been used successfully with the A1200 beam analysis device at the NSCL of Michigan State University. This program provides rough order of magnitude estimates of the beam rates as well as information on the proper settings for the separator thereby making the process of tuning a radioactive beam much simpler.

The main difficulty in adapting the INTENSITY program lies in differences between a doubly achromatic magnetic separator using projectile fragmentation such as the A1200⁴ and the combined magnetic separation and velocity filter of the MARS system. These differences include:

1. Production Mechanism - In INTENSITY, the production mechanism is assumed to be projectile fragmentation. However, for MARS, the primary production mechanism will involve transfer reactions. These reactions are somewhat more difficult to model in a simple way. For projectile fragmentation, there exist simple parameterizations which allow the program to provide estimates of the production cross sections as well as the widths of the momentum and angular distributions. For transfer reactions, no simple universal parameterizations are available. Instead, the program will need to read in this information from an input file generated by other programs, and use this information to determine the total production rate and beam characteristics leaving the target.
2. Beam Optics - The INTENSITY program uses first order beam optics to transfer the beam parameters through the system. This is simplified by the fact that the only positions considered are images where most of the cross terms in the transport matrix are zero. The distributions which are generated can then be used to apply the physical cuts made by the system to determine the fraction of the beam produced in the target which reaches the final image. For the MARS system, the beam optics are somewhat more complicated, requiring significant second order corrections to obtain the optimum resolution.^{1,2} However, the first order optics may be sufficient to provide the rough estimates desired.
3. Wein Filter - INTENSITY is based on a totally magnetic system where the physical dispersion of the beam is obtained solely from its momentum dispersion. This is true even when an achromatic degrader wedge⁵ is used to obtain additional separation. For the MARS system, the use of the velocity filter requires expansion of the beam optics to include the mass and velocity dispersions as well as the momentum dispersion. However, both systems can be viewed as being similar since they involve a magnetic separation according to p/q (momentum to charge ratio) followed by an additional separation. The only difficulty lies in how to include the secondary separation. In

general, the MARS system will be considered in two stages: the first stage being the magnetic separation according to p/q with the second stage being the velocity filter. This simplifies analysis of the system to just three positions: target, dispersive image, and final image.

4. Lower Beam Energy - Since the beams available from the K500 cyclotron are somewhat lower in energy than those considered in the design of the INTENSITY program, changes may be necessary in the various energy loss, scattering, and charge state distribution calculations for good results to be obtained.

These differences are being considered in detail at the present as plans are being formulated as to the best method for modifying the program.

A major advantage of a program such as INTENSITY lies in the ability to estimate the proper settings for the separator. This information greatly reduces the time required to identify, optimize, and achieve the best separation for a radioactive beam under any set of conditions. An additional advantage lies in the programs "user friendly" environment which involves the use of a set of menus which can be easily followed with only minimal instruction. In addition, it does not require the user to construct any complicated input files in order for the program to be useful. (The primary input files are either in existence, or can be generated by the program itself.) Although adapting the program to be used with the MARS system may require adopting the use of some additional input files (input of production cross sections is already available), we will strive to make the production of these files available from additional menu driven programs. Finally, the program contains a large number of sub-units which allow calculation of energy losses, multiple scattering, ranges, etc. These sub-units are also easily accessible through the menu system and provide

important information for understanding results being obtained in an experiment.

The development of the MDM analysis system at the Cyclotron Institute will allow the production and use of radioactive ion beams in experimental devices not easily coupled to the MARS system. Since the MDM system will be similar in design to the A1200, the INTENSITY program will be easily adapted to this new system. Doing this, we will then be able to make useful predictions concerning the intensities of radioactive beams which could be used for various secondary interaction experiments.

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MDM Spectrometer

D. H. Youngblood, Y. W. Lui, J. D. Bronson, G. Hendricks, and D. Borovino

Installation of the MDM spectrometer, constructed at Oxford University,¹ has proceeded approximately as planned except for one major change. When assembly of the dipole was nearly complete in mid August, it became apparent that the spectrometer could be lowered with a modification of the base assembly so that the height of its median plane was the same as that of the K500 cyclotron and all our beam lines. As constructed at Oxford, the MDM median plane was some 22 inches higher than that of the cyclotron, and it appeared from the drawings that many items would have to be rebuilt to lower it to the K500 median plane, so we planned to use two bending magnets to raise the beam.

Although these bending magnets had already been constructed, we chose to disassemble the MDM and modify the base assembly to simplify the beam optics for the spectrometer. The two dipoles, with some modifications, can be used in the beam analysis system. This caused a delay in the project of about 5 weeks. Modifications to the target chamber mount, the target height control assembly, and the multipole mount were also required. A new support system for the exit multipole and the detector box were designed and constructed.

Most components of the spectrometer were disassembled, cleaned, painted as appropriate and reassembled with new rubber hoses, and vacuum seals in the spring and early summer by undergraduate physics majors. The Enge split-pole spectrometer was removed in June and shipped to CEBAF to serve as part of a tagged photon facility. An epoxy floor was poured in place for the air bearing. The wall plug which carries the beam through the wall from the 88 cyclotron vault to Cave 3 was moved to the correct position for the spectrometer.

The air compressor for the air bearing, vacuum pumps for the spectrometer and target chamber, and power supplies for the entrance and exit multipoles were all obtained in the spring.

Three test runs have already been carried out in the MDM spectrometer. During the first in

February, beam was brought to the MDM scattering chamber as a test of the beam optics. An appropriate focus was successfully obtained. During the second run in March the beam was taken around the spectrometer to a phosphor located just after the exit multipole. Proper operation of the dipole and of the entrance multipole were verified. During the third run in April, 40 MeV/nucleon ^{14}N ions were passed through Pb, C and Zr foils and scattered particles detected in the focal plane. A scintillator has been added to the hybrid detector built at Oxford² and initial experiments will use this system. Numerous spectra were obtained studying the behavior of the detector at several pressures and voltages and the behavior of the spectrometer with various slits at the exit of the target chamber. Figure 1 shows an ionization chamber spectrum and reasonable particle separation can be seen. These data are now being analyzed. Several minor problems with the detector and electronics were identified.

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Figure 1. Ionization chamber spectrum showing reasonable particle separation.

Barium Fluoride Array

H. Jabs, M. Murray, and K. L. Wolf

Background levels and beam tuning parameters were investigated for a new scattering chamber location on beamline 2b (in cave 2 of the new K500 area). The location is designated for short term target chamber installation, and is well suited for those experiments that require a remote beam dump and downstream refocusing for low background applications. One of the nineteen-pack arrays of the BaF_2 system¹ was used to scan along the beamline in self-triggered mode with a gamma ray threshold of 1 MeV. A 30 AMeV ^{16}O beam produced background mainly from the beam dump (located 4.1 m from the target) which will be shielded in future experiments. A beam spot size of 3×3 mm at the target location was obtained with a parallel optics solution.

Photon data were taken with a 1 mg/cm^2 ^{197}Au target in self triggered and in fission fragment-photon coincidence modes. The latter trigger used a 4 cm^2 silicon heavy-ion detector for fission fragment detection to produce photon data that were free of background from the beam dump and from cosmic rays. Data were collected in 70 parameter event mode with a 80386-based PC interfaced to CAMAC and with a LeCroy 2280 ADC system. The computer deadtime was typically 7% at a beam current of 2na. Fast format CAMAC charge sensitive ADCs purchased for the BaF_2 arrays from Phillips Scientific Inc. contain design errors that do not allow use with the required $2 \mu\text{s}$ gate widths for the slow component of the BaF_2 signals. The energy calibration was made with ^{60}Co and PuBe sources and was extrapolated to high energies with a precision pulser. All electronics except the computer and scalers were located with the detectors in the beam area.

Figure 1 shows a photon energy spectrum taken with the BaF_2 array situated 47 cm from the target at an angle of 90° . Low energy neutron background was minimized with a window on the BaF_2 time of flight spectrum from each crystal. The TDC spectra used a Spieler time pickoff unit on the silicon detector for a fission fragment reference signal and showed an overall photon-fragment time resolution of 200 ps. Contributions from high energy neutrons and pulse pile-up were eliminated with pulse shape

discrimination based on the ratio of fast/slow pulse height response from the BaF_2 . A 20 ns gate width was used for the fast component signal with a shortest possible 140 ns cable delay to minimize pulse shape distortion. The spectrum was fitted with a two-component exponential that yielded results for the low energy component (statistical emission) and for the bremsstrahlung-associated high energy component. The inverse slope value of approximately 12 MeV for the high energy tail of the spectrum agrees with systematics.² The structure at intermediate energy is in the giant dipole resonance region. The background subtracted spectrum is made much narrower ($\text{FWHM}=5 \text{ MeV}$ at $E=19 \text{ MeV}$), as expected for the GDR when a window is set on the central region of the fission fragment pulse height distribution, corresponding to symmetric mass splits, approximately $A = 100\text{-}110$.

Figure 1. Photon spectrum for 30 MeV $^{16}\text{O} + ^{197}\text{Au}$ reaction at 90° in the laboratory. Fission fragment coincidence was required with a 4 MeV threshold on the gamma ray summed energy.

References

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The 4 π CsI Ball

B. Xiao, G. Derrig, K. Hagel, R. Tezkratt, R. Wada, J. B. Natowitz, J. Li, Y. Lou, D. Uteley

In the past year, we have continued our work on the 4 π CsI detector which will be used in conjunction with the ORNL Heavy Ion Light Ion (HILI) detector and the Texas A&M University 4 π Neutron Ball to provide a detector system for heavy ion reactions. Following is a report on the progress we have made on the construction of the CsI Ball since last year's Annual Report. We divide our discussion into four sections. In section I, we will discuss the PMT Base (voltage divider) design. The Data Acquisition Electronics we used in the test run are discussed in section II. The results of the test for particle identification and the test for light collection are shown in section III. Finally we briefly report the status of the mechanical construction of the CsI Ball in section IV.

Figure 1. Photomultiplier voltage divider. $R1 = R10 = R11 = 160\text{ k}\Omega$; $R3 = R7 = R8 = 60\text{ k}\Omega$; $R2 = R4 = R5 = R6 = 41\text{ k}\Omega$; $R9 = 80\text{ k}\Omega$; $C1 = C4 = 0.1\text{ }\mu\text{F}$; $C2 = 0.2\text{ }\mu\text{F}$; $C3 = 0.3\text{ }\mu\text{F}$.

I. PMT Base

A considerable effort has been made to design the proper PMT voltage divider. First we considered both the active base used in the MSU Miniball¹ and a passive voltage divider. We have obtained better particle resolution with the latter. We tested several passive voltage dividers with different resistor chains suggested by HAMAMATSU. Figure 1 shows the diagram for the divider we finally chose. This base, suggested by HAMAMATSU for improving linearity,

gave us much better particle identification than the others. The test results are shown in section IV.

ATT: Attenuator
CFDD: Constant Fraction Discriminator
F/F: Linear Fan-in Fan-out
GDG: Gate and Delay Generator
QDC: Charge-sensitive (current-integrating) ADC
PMT: Photomultiplier Tube

Gate Width
Gate 1: 50ns
Gate 2: 400ns
Gate 3: 1 μ s

Figure 2. Schematic diagram of signal processing and trigger logic scheme.

II. Data Acquisition Electronics

A block electronics diagram of the signal processing and trigger logic scheme used in the test run is shown in Figure 2. The anode signal from the PMT is divided via a linear fan-in fan-out into four branches: "plastic," "fast component of CsI," "slow component of CsI," and the branch which is used to create the gates and trigger. Each of the "signal" branches goes through an attenuator before it enters the charge-sensitive (current-integrating) ADC (QDC), so that we can adjust the attenuation factor to get the proper relative amplitudes between them. The 50 ns wide plastic gate (gate 1) is created directly by the constant fraction discriminator (CFD). The 400 ns fast gate (gate 2) and the 1 μ s slow gate (gate 3) are created by gate and delay generators (GDG), and are 15ns and 1 μ s delayed from the plastic gate, respectively. The trigger is delivered from the CFD. This set up constitutes the Pulse-

Shape-Discrimination method described in section III.

Figure 3. Energy spectra of ^{252}Cf - α and ^{148}Gd - α at different positions. (a): Cf source at pos. 1; (b): Cf source at pos. 4; (c): Cf source at pos. 3; (d): Gd source at pos. 4.

III. Test Results

Two types of test were done in the past year.

The first test was for the light collection efficiency of the light guide to be used for the 90° detector. The geometry of the light guide can be found in last year's Annual Report.² A CsI crystal ($5\text{cm} \times 6\text{cm} \times 5\text{mm}$) is glued by silicon rubber on the front surface of the light guide. The whole element is wrapped by an aluminized mylar foil ($200\mu\text{g}/\text{cm}^2$). In Figure 3, the energy spectra of ^{252}Cf - α (6.1 MeV) and ^{148}Gd - α (3.1 MeV) at different positions on the front surface of the CsI crystal are plotted. Positions are indicated in the upper right part of Fig. 4. The results are summarized in Fig. 4. No significant position dependence of the mean energy has been observed, although the width increase from position 1 to 4 is observed.

Figure 4. Test result for light collection efficiency of the light guide at 90° .

In the test for particle identification, we use the Pulse-Shape-Discrimination technique. Figure 5 shows how we choose the gates for the plastic signal, fast component of the CsI signal, slow component of the CsI signal, and delay time between these gates. The NE102 plastic scintillator ($100\mu\text{g}/\text{cm}^2$) is laid directly on the CsI crystal (2 cm long and 1 inch diameter) surface. The photomultiplier tube is an HAMAMATSU R1924 and the base is the one we described in section I. The data acquisition electronics is discussed in section II. The high voltage applied on the PMT is -1000 volts. The

Figure 5. Schematic picture of the detector and Pulse-Shape-Discriminator technique for particle identification.

attenuation factors for the plastic, fast, and slow branches are 0.5, 0.1, and 0.7, respectively. A 20 MeV/u ^{40}Ar beam from the Texas A&M K-500 superconducting cyclotron has been used to bombard at ^{nat}Ag target during the test. The detector was set at 15° about 20 cm from the target position. Figure 6(a) shows a scatter plot of the fast component vs. slow component of the CsI signal. The slow component of the CsI signal vs. plastic signal is shown in Fig. 6(b). We can see nice p,d,t separation in Fig. 6(a). Good charged particle identification has been observed in Fig. 6(b) with low CsI signal, but not with the higher CsI signal. Further tests are underway to solve this problem.

IV. Mechanical Construction

Detailed designs of the CsI crystals and light guides can be found in last year's Annual Report. All the CsI crystals, which were manufactured by Bicron and PMTs from HAMAMATSU arrived recently. The light guides will be finished shortly. We also finished the detailed design of the chamber in the past year. The machining of the chamber will be completed in the very near future.

Figure 6. Test result for particle identification in the reaction 20 MeV/u $^{40}\text{Ar} + \text{Ag}$. 6(a): fast component of CsI vs. slow component of CsI; 6(b): slow component of CsI vs. plastic.

References

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2. B. Xiao *et al.*, *Progress in Research, 1991-1992*, Cyclotron Institute, TAMU, p. 126.

PUBLICATIONS

ABSTRACTS OF PAPERS PUBLISHED

April, 1992 - March, 1993

ANTIPROTON PRODUCTION IN RELATIVISTIC Si-NUCLEUS COLLISIONS

J. Barrette, R. Bellwied, P. Braun-Munzinger, W. E. Cleland, T. Cormier, G. Dadusc, G. David, J. Dee, G. E. Diebold, O. Dietzsch, E. Duek, M. Fatyga, D. Fox, S. V. Greene, J. V. Germani, J. R. Hall, T. K. Hemmick, N. Herrmann, R. W. Hogue, B. Hong, K. Jayananda, D. Kraus, B. S. Kumar, R. Lacasse, D. Lissauer, W. J. Llope, T. W. Ludlam, R. Majka, D. Makowiecki, S. K. Mark, J. T. Mitchell, M. Muthuswamy, E. O'Brien, C. Pruneau, F. S. Rotondo, J. Sandweiss, N. C. da Silva, J. Simon-Gillo, J. Slaughter, U. Sonnadara, J. Stachel, H. Takai, E. M. Takagui, T. G. Throwe, L. Waters, Ch. Winter, K. Wolf, D. Wolfe, C. L. Woody, N. Xu, Y. Zhang, Z. Zhang, and C. Zou
Phys. Rev. Lett. **70**, 1763 (March, 1993)

We have measured antiproton production cross sections as functions of centrality in collisions of 14.6 GeV/c per nucleon ^{28}Si ions with targets of Al, Cu, and Pb. For all targets, the antiproton yields increase linearly with the number of projectile nucleons that have interacted, and show little target dependence. We discuss the implications of this result on the production and absorption of antiprotons within the nuclear medium.

M_T SCALING IN DILEPTON SPECTRUM AS A SIGNATURE FOR QUARK-GLUON PLASMA

M. Asakawa, C. M. Ko, and P. Lévai
Phys. Rev. Lett. **70**, 398 (January, 1993)

In general, the spectrum of lepton pairs produced in nuclear reactions depends on both invariant mass and momentum. But under a few reasonable assumptions on the time evolution of the system, we show that once the quark-gluon plasma is created in ultrarelativistic heavy ion collisions, the observed dilepton spectrum between the ϕ and J/ψ peak becomes dependent essentially only on its transverse mass M_T and thus shows M_T scaling. This scaling

will not be observed if the quark-gluon plasma is not created in collisions.

EVIDENCE AGAINST A 17 keV NEUTRINO FROM ^{35}S BETA DECAY

J. L. Mortara, I. Ahmad, K. P. Coulter, S. J. Freedman, B. K. Fujikawa, J. P. Greene, J. P. Schiffer, W. H. Trzaska, and A. R. Zeuli
Phys. Rev. Lett. **70**, 394 (January, 1993)

We have searched for the effects of a neutrino of mass 17 keV/c² in the beta decay of ^{35}S with an apparatus incorporating a high-resolution solid-state detector and a superconducting solenoid. The experimental mixing probability, $\sin^2\theta = -0.0004 \pm 0.0008(\text{stat}) \pm 0.0008(\text{syst})$, is consistent with zero, in disagreement with several previous experiments. Our sensitivity to neutrino mass is verified by measurements with a mixed source of ^{35}S and ^{14}C , which artificially produces a distortion in the beta spectrum similar to that expected from the massive neutrino.

MULTIFRAGMENTATION OF $^{40}\text{Ca} + ^{40}\text{Ca}$

K. Hagel, M. Gonin, R. Wada, J. B. Natowitz, B. H. Sa, Y. Lou, M. Gui, D. Utley, G. Nebbia, D. Fabris, G. Prete, J. Ruiz, D. Drain, B. Chambon, B. Cheynis, D. Guinet, X. C. Hu, A. Demeyer, C. Pastor, A. Giorni, A. Lleres, P. Stassi, J. B. Viano, and P. Gonthier
Phys. Rev. Lett. **68**, 2141 (April 1992)

The multifragment emission of "completely characterized" events in the $^{40}\text{Ca} + ^{40}\text{Ca}$ system at 35 MeV/nucleon has been compared to the predictions of several models. The observed multifragment emission is not in agreement with models based on conventional statistical binary decay, but is in agreement with both a simultaneous multifragmentation model and a sequential emission model in which expansion is treated.

RESIDUE TEMPERATURES AND THE NUCLEAR EQUATION OF STATE

H. M. Xu, P. Danielewicz, and W. G. Lynch
Phys. Lett. **299B**, 199 (January, 1993)

Excitation energies are calculated for heavy residues produced in central $^{40}\text{Ar} + ^{124}\text{Sn}$ collisions for a range of incident energies and impact parameters using the BUU transport equation. These excitation energies are evaluated at freezeout times determined from the time dependence of the thermal excitation energy and the nucleon emission rate. Both the thermal excitation energies and temperatures, obtained assuming Fermi gas level densities, are sensitive to the nuclear equation of state and the impact parameter. Surprisingly little sensitivity is observed to the in-medium nucleon-nucleon cross section.

MOMENTUM DEPENDENCE IN PAIR PRODUCTION BY AN EXTERNAL FIELD

M. Asakawa
Phys. Lett. **287B**, 165 (August, 1992)

The transverse and the longitudinal momentum dependences of the pair production under an adiabatically exerted uniform abelian external field are calculated with their importance in models for the production of quark-gluon plasma in ultrarelativistic heavy ion collisions in mind. The importance of the initial condition is revealed. We show that superposition of acceleration by the external field and barrier penetration is reflected in the longitudinal momentum dependence. The peculiar nature of the boost invariant system which is expected to be approximately realized in ultrarelativistic nuclear collisions is pointed out.

PION MULTIPLICITY AS A PROBE OF THE DECONFINEMENT TRANSITION IN HEAVY-ION COLLISIONS

M. I. Gorenstein, S. N. Yang, and C. M. Ko
Phys. Lett. **281B**, 197 (May, 1992)

The hydrochemical model is used to calculate the pion multiplicity in relativistic heavy-ion collisions. Chemical reactions are explicitly taken into account

in the expansion stage of the hadronic phase. It leads to the absence of chemical equilibrium among hadronic particles and a nonzero value of the pion chemical potential at thermal freeze out. We find a specific structure in the incident energy dependence of the pion multiplicity as a result of the formation of the quark-hadron mixed phase in the initial stage of the collision.

NUCLEAR MATTER COMPRESSIBILITY FROM ISOSCALAR GIANT MONOPOLE RESONANCE

S. Shlomo and D. H. Youngblood
Phys. Rev. C **47**, 529 (February, 1993)

We examine the status of the nuclear matter compressibility K_{nm} obtained from experimental data of the strength distribution of the giant monopole resonance in nuclei and employing a least-squares fit to a semiempirical expansion of the nucleus compressibility K_A in $A^{-1/3}$. We present arguments indicating that all the coefficients of this expansion must be determined by a fit to the data. In our analysis we have used the entire data set, correcting for systematic energy differences between data sets measured in different laboratories, and applying the same criteria to all sets in extracting the uncertainties. Contrary to recent statements by Sharma and collaborators, we find that the present complete data set is not adequate to limit the range of K_{nm} to better than about a factor of 1.7 (200 to 350 MeV).

TRANSPORT MODEL WITH QUASIPIONS

L. Xiong, C. M. Ko, and V. Koch
Phys. Rev. C **47**, 788 (February, 1993)

We extend the normal transport model to include the medium effect on pions by treating them as quasiparticles. The property of the quasipion is determined using the delta-hole model. Modeling heavy-ion collisions at intermediate energies with the new transport equations, we find that it leads to an enhanced production of pions with low kinetic

energies. This gives a plausible explanation for the observed enhancement of soft pions in the Bevalac experiments.

DISAPPEARANCE OF ROTATION IN HEAVY-ION COLLISIONS

H. M. Xu

Phys. Rev. C 47, 891 (February, 1993)

The azimuthal distributions of nucleons are studied for central $^{40}\text{Ar} + ^{51}\text{V}$ collisions from $E/A = 35$ to 125 MeV based on a Boltzmann equation. We demonstrate that the contribution to azimuthal asymmetry from residue rotation decreases with incident energy and eventually vanishes at energies $E/A \geq 75$ MeV. In contrast, the contribution from the directed transverse motion remains important throughout the energy range investigated. We show that the disappearance of rotation is mainly associated with the onset of multifragmentation for which the thermal instabilities appear to play a minor role.

DIFFERENTIAL CROSS SECTION FOR n - p ELASTIC SCATTERING IN THE ANGULAR REGION $50^\circ < \theta^* < 180^\circ$ AT 459 MeV

L. C. Northcliffe, M. Jain, M. L. Evans, G. Glass, J. C. Hiebert, R. A. Kenefick, B. E. Bonner, J. E. Simmons, C. W. Bjork, and P. J. Riley
Phys. Rev. C 47, 36 (January, 1993)

The differential cross section for n - p elastic scattering at 459 MeV in the c.m. angular region $50^\circ < \theta^* < 180^\circ$ has been measured with high statistical precision and good relative accuracy. The uncertainty in the absolute normalization (based on the simultaneously measured yield of deuterons from the $np \rightarrow d\pi^0$ reaction) was initially estimated to be $\sim 7\%$. The results agree well with back-angle data obtained independently at LAMPF but less well with results from Saclay and the Princeton-Pennsylvania Accelerator and, except for a normalization difference of 10%, are fairly well represented by a phase-shift fit. The pole-extrapolation method of Chew was used to extract the pion-nucleon coupling constant f^2 from the back-angle portion of the data. The value obtained, $f^2 = 0.069$, is somewhat smaller than the values 0.0735-0.0790 obtained from analyses

of pion-nucleon scattering, tending to confirm the need for an upward renormalization of the angular distribution by $\sim 10\%$.

MASS ASYMMETRY, EQUATION OF STATE, AND NUCLEAR MULTIFRAGMENTATION

H. M. Xu

Phys. Rev. C 46, R2144 (December, 1992)

Multifragmentation is observed with an improved Boltzmann-Uehling-Uhlenbeck model for $^{40}\text{Ar} + ^{51}\text{V}$ and $^{92}\text{Mo} + ^{92}\text{Mo}$ collisions. For ^{12}C induced reactions, however, a single residue is observed up to energy $E/A \approx 200$ MeV. By investigating the dependence on the masses of the projectile and target and on the equation of state, we demonstrate that the dynamics of compression and expansion, rather than the thermal excitation energy, plays the dominant role in causing the observed multifragmentation.

EXPLORING THE VALIDITY OF $Z=38$ AND $Z=50$ PROTON CLOSED SHELLS IN EVEN-EVEN Mo ISOTOPES

H. Dejbakhsh, D. Latypov, G. Ajupova, and S. Shlomo

Phys. Rev. C 46, 2326 (December, 1992)

Energy spectra, $B(E2)$ values, and ratios of the neutron-rich even-even Mo isotopes in the mass 100 region have been investigated in terms of the neutron-proton interacting boson model. Two different approaches were used. The first investigation is based on the validity of the $Z=38$ subshell closure considering ^{88}Sr as a doubly magic core. In the second calculation $Z=50$ and $N=50$ were considered as valid closed shells leading to ^{100}Sn as a core. The results from both calculations are compared with experimental data.

RHO MESON IN DENSE HADRONIC MATTER

M. Asakawa, C. M. Ko, P. Lévai, and X. J. Qiu
Phys. Rev. C 46, R1159 (October, 1992)

The spectral function of a rho meson that is at rest in dense hadronic matter and couples strongly to the pion is studied in the vector dominance model by including the effect of the delta-hole polarization on the pion. With the free rho-meson mass in the

Lagrangian, we find that both the rho-meson peak and width increase with increasing nuclear density, and that a low-mass peak appears at invariant mass around three times the pion mass. Including the decreasing density-dependent hadron masses in the Lagrangian as suggested by the scaling law of Brown and Rho, we find instead that the rho peak moves to smaller invariant masses with diminishing strength when the nuclear density increases. The low-mass peak also shifts down with increasing density and becomes more pronounced. The relevance of the rho-meson property in dense matter to dilepton production in heavy-ion collisions is discussed.

ANTILAMBDA ENHANCEMENT IN ULTRARELATIVISTIC HEAVY ION COLLISIONS

C. M. Ko, M. Asakawa, and P. Lévai
Phys. Rev. C **46**, 1072 (September, 1992)

In the Walecka model, the antilambda mass in dense nuclear matter is smaller than its value in free space. This reduces the threshold for antilambda production in dense matter that forms in the compression stage of ultrarelativistic heavy ion collisions. Because of the large number of mesons produced in the collision, the process $KM \rightarrow \bar{\Lambda}N$, where M denotes either a pion or a rho meson, is shown to be important and provides thus a plausible explanation for the observed enhancement of antilambda yield in recent experiments carried out at CERN SPS with nuclear beams.

DISAPPEARANCE OF FLOW AND THE IN- MEDIUM NUCLEON-NUCLEON CROSS SECTION

H. M. Xu
Phys. Rev. C **46**, R389 (August, 1992)

Based on a Boltzmann equation, the transverse momentum distributions are calculated for central $^{40}\text{Ar} + ^{51}\text{V}$ collisions with an aim to determine the in-medium nucleon-nucleon cross section. Indeed, the calculations suggest that measurements of the energy of balance, E_{bal} , can provide a powerful tool to pin down the in-medium nucleon-nucleon cross section. Within our improved Boltzmann-Uehling-Uhlenbeck (BUU) model, the in-medium nucleon-nucleon cross

section is narrowed down to $\sigma_{\text{NN}} \approx 30\text{-}40$ mb, for the first time, using recent experimental data.

K^+ TOTAL CROSS SECTIONS ON ^{12}C AND MEDIUM EFFECTS IN NUCLEI

R. A. Krauss, J. Alster, D. Ashery, S. Bart, R. E. Chrien, J. C. Hiebert, R. R. Johnson, T. Kishimoto, I. Mardor, Y. Mardor, M. A. Moinester, R. Olshevsky, E. Piasetsky, P. H. Pile, R. Sawaf, R. L. Stearns, R. J. Sutter, R. Weiss, and A. I. Yavin
Phys. Rev. C **46**, 655 (August, 1992)

The total cross sections for K^+ mesons on carbon and deuterium nuclei have been measured at eleven momenta in the range 450-740 MeV/c. The experimental technique was of the standard transmission type. The K^+ meson is the least strongly interacting of available hadronic probes, with a long mean free path in nuclear matter. At low incident momentum the K^+N interaction is dominated by the S_{11} phase shift and varies slowly with energy. These characteristics make the K^+ an ideal tool for probing the nuclear volume to reveal nuclear medium effects. Measurements of the ratio of the total cross sections, per nucleon, of $K^+ - ^{12}\text{C}$ to $K^+ - d$ have been suggested as a way to reveal effects of the nuclear medium. The total cross section ratios are found to lie significantly above those predicted by the usual nuclear medium corrections. This suggests that novel phenomena are taking place within the nucleus. Several models which incorporate such phenomena are discussed, including nucleon "swelling," mass rescaling, nuclear pions, and relativistic effects.

CHARGED PARTICLE MULTIPLICITY IN ^{28}Si + Al, Cu, AND Pb REACTIONS AT $E_{\text{lab}} = 14.6$ GeV/nucleon

J. Barrette, R. Bellwied, P. Braun-Munzinger, W. E. Cleland, G. David, O. Dietzsch, E. Duek, M. Fatyga, D. Fox, S. V. Greene, J. R. Hall, R. Heifetz, T. K. Hemmick, M. Herman, N. Hermann, R. W. Hogue, G. Ingold, K. Jayananda, D. Kraus, S. Kumar, R. Lacasse, D. Lissauer, W. J. Llope, T. Ludlam, R. Majka, D. Makowiecki, S. K. Mark, S. R. McCorkle, J. T. Mitchell, M. Muthuswamy, E. O'Brien, L. Olsen, V. Polychronakos, C. Pruneau, M. Rawool-Sullivan, F. Rotondo, J. Sandweiss, J.

Simon-Gillo, U. Sonnadara, J. Stachel, J. P. Sullivan, J. Sunier, E. M. Takagui, H. Takai, T. Throwe, H. van Hecke, L. Waters, K. Wolf, D. Wolfe, C. L. Woody, N. Xu, and Z. Zhang
Phys. Rev. C **46**, 312 (July, 1992)

Collisions of $^{28}\text{Si} + \text{Al}$, Cu , and Pb at $E_{\text{lab}} = 14.6$ GeV/nucleon were studied at the Brookhaven National Laboratory Alternating Gradient Synchrotron. Charged particle multiplicity was measured over the pseudorapidity interval $0.875 \leq \eta \leq 3.86$ with a silicon pad detector. A strong correlation is seen between the multiplicity and the transverse energy measured in the interval $-0.5 \leq \eta \leq 0.8$. Correlation with the energy going forward after the collision and comparison with calculations indicate that rescattering is required to explain the data. The data are compared under the assumption of Koba-Nielson-Olesen scaling. The measured multiplicity scales approximately with the total number of participant nucleons and less well with the available center-of-mass kinetic energy.

np ELASTIC SPIN-TRANSFER MEASUREMENTS AT 485 AND 635 MeV

K. H. McNaughton, D. A. Ambrose, P. Coffey, K. Johnston, P. J. Riley, M. W. McNaughton, K. Koch, I. Supek, N. Tanaka, G. Glass, J. C. Hiebert, L. C. Northcliffe, A. J. Simon, D. J. Mercer, D. L. Adams, H. Spinka, R. H. Jeppesen, G. E. Tripard, and H. Woolverton
Phys. Rev. C **46**, 47 (July, 1992)

We have measured the spin-transfer parameters K_{LL} , K_{SL} , K_{LS} , and K_{SS} at 635 MeV from 50° to 178° c.m. and at 485 MeV from 74° to 176° c.m. These new data have a significant impact on the phase-shift analyses. There are now sufficient data near these energies to overdetermine the elastic nucleon-nucleon amplitudes.

$^3\text{H}(p,n)2p$ SPIN TRANSFER FROM 305 TO 788 MeV

M. W. McNaughton, K. Koch, I. Supek, N. Tanaka, D. A. Ambrose, P. Coffey, K. Johnston, K. H. McNaughton, P. J. Riley, G. Glass, J. C. Hiebert, L. C. Northcliffe, A. J. Simon, D. J. Mercer, D. L.

Adams, H. Spinka, R. H. Jeppesen, G. E. Tripard, and H. Woolverton
Phys. Rev. C **45**, 2564 (June, 1992)

Measurements of the spin-transfer parameter K_{LL} for $^3\text{H}(p,n)2p$ at 0° to calibrate the neutron-beam polarization clarify a normalization discrepancy affecting np data at LAMPF. The new data are in good agreement with theoretical predictions.

ELECTROMAGNETIC DISSOCIATION OF RELATIVISTIC ^{28}Si INTO $p+^{27}\text{Al}$

J. Barrette, R. Bellwied, P. Braun-Munzinger, W. E. Cleland, G. David, J. Dee, O. Dietzsch, E. Duek M. Fatyga, D. Fox, S. V. Greene, J. R. Hall, T. K. Hemmick, N. Herrmann, R. W. Hogue, B. Hong, K. Jayananda, D. Kraus, B. Shiva Kumar, R. Lacasse, D. Lissauer, W. J. Llope, T. Ludlam, R. Majka, D. Makowiecki, S. K. Mark, S. McCorkle, J. T. Mitchell, M. Muthuswamy, E. O'Brien, V. Polychronakos, C. Pruneau, F. S. Rotondo, J. Sandweiss, J. Simon-Gillo, U. Sonnadara, J. Stachel, H. Takai, E. M. Takagui, T. G. Throwe, L. Waters, W. J. Willis, C. Winter, K. Wolf, D. Wolfe, C. L. Woody, N. Xu, Y. Zhang, Z. Zhang, and Z. Zou
Phys. Rev. C **45**, 2427 (May, 1992)

We report a direct measurement of the final-state energy spectrum in the electromagnetic dissociation of ^{28}Si into $p+^{27}\text{Al}$ at an energy of 14.6 GeV/nucleon. The final-state energy is obtained through a calculation of the $p-^{27}\text{Al}$ invariant mass in kinematically reconstructed events. The final-state energy spectrum for all targets is peaked near the isovector giant-dipole resonance in ^{28}Si and the dependence of the magnitude of the cross section on target charge confirms that the excitation is largely electromagnetic. By exploiting the expected scaling behavior on target Z and A , the background from nuclear interactions is evaluated and subtracted, leaving a pure electromagnetic dissociation final-state energy distribution. This distribution is well reproduced by simulated events, in which the photon spectrum calculated in the Weizsäcker-Williams approximation is combined with experimental data on the photonuclear reaction $^{28}\text{Si}(\gamma,p)^{27}\text{Al}$, and slight differences are observed only at low final-state energy.

GIANT QUADRUPOLE RESONANCE IN NI ISOTOPES

D. H. Youngblood, Y.-W. Lui, U. Garg, and
R. J. Peterson
Phys. Rev. C **45**, 2172 (May, 1992)

Inelastic scattering of 129 MeV alpha particles has been used to excite the giant quadrupole resonance in $^{58,60,62,64}\text{Ni}$. The resonance was found to exhaust $58 \pm 12\%$, $76 \pm 14\%$, $78 \pm 14\%$, and $90 \pm 16\%$ of the $E2$ energy-weighted sum rule, respectively, for $^{58,60,62,64}\text{Ni}$.

DYNAMICAL ASPECTS OF INTERMEDIATE MASS FRAGMENT EMISSION IN THE REACTION OF $^{32}\text{S} + \text{Ag}$ AT $30 \text{ A} \cdot \text{MeV}$

R. Wada, M. Gonin, M. Gui, K. Hagel, Y. Lou, D. Utley, B. Xiao, D. Miller, J. B. Natowitz, D. Fabris, G. Nebbia, R. Zanon, B. Chambon, B. Cheynis, A. Demeyer, D. Drain, D. Guinet, X. C. Hu, C. Pastor, K. Zaid, J. Alarja, R. Bertholet, A. Giorni, A. Lleres, C. Morand, P. Stassi, L. Schussler, B. Viano, P. Gonthier
Nucl. Phys. A**548**, 471 (October, 1992)

The emission of intermediate mass fragments (IMFs) has been studied using the 4π array, AMPHORA. The energy spectra, the angular distributions, the multiplicities, and the charge distributions are studied inclusively as well as in coincidence with projectile-like fragments (PLFs) and other fragments. The low-energy component of the inclusive fragment spectra can be reproduced by a statistical binary decay code GEMINI, although the calculated absolute cross sections are an order of magnitude smaller than the experimental IMF cross sections. At intermediate angles the fragments are dominated by IMFs with $Z \leq 10$ both for inclusive and coincidence events and the energy spectra of the fragments show hard components which cannot be explained as statistical emission. For this non-equilibrium component strong azimuthal angular correlations are observed in IMF-PLF and IMF-IMF coincidence events. Both the energy spectra and the azimuthal angular correlations of the non-equilibrium component are well reproduced by the extended classical dynamical model.

ANTIPROTON PRODUCTION IN ^{28}Si -NUCLEUS INTERACTIONS

J. Barrotte, R. Bellwied, P. Braun-Munzinger, W. E. Cleland, T. Cormier, G. David, J. Dee, O. Dietzsch, E. Duek, M. Fatyga, D. Fox, S. V. Greene, J. R. Hall, T. K. Hemmick, N. Herrmann, R. W. Hogue, B. Hong, K. Jayananda, D. Kraus, B. Shiva Kumar, R. Lacasse, D. Lissauer, W. J. Llope, T. Ludlam, R. Majka, D. Makowiecki, S. K. Mark, S. McCorkle, J. T. Mitchell, M. Muthuswamy, E. O'Brien, V. Polychronakos, C. Pruneau, F. S. Rotondo, J. Sandweiss, N. C. da Silva, J. Simon-Gillo, J. Slaughter, U. Sonnadara, J. Stachel, H. Takai, E. M. Takagui, T. G. Throwe, L. Waters, C. Winter, K. Wolf, D. Wolfe, C. L. Woody, N. Xu, Y. Zhang, Z. Zhang, and C. Zou
Nucl. Phys. A**544**, 599c (July, 1992)

We have used the E814 apparatus to make a systematic study of antiproton production in collisions of ^{28}Si ions at $14.6 \text{ GeV}/c$ per nucleon with targets of Pb, Cu, and Al. We have measured the antiproton yield per interaction as a function of transverse energy and have found the yield to increase by a factor of ≈ 2 in going from the least to the most central collisions on the Pb target. A simple first-collision picture of antiproton production predicts the yield to increase by a factor of ≈ 11 . We suggest that the discrepancy may result from the annihilation of antiprotons within the nuclear medium.

MOMENTUM DISTRIBUTIONS OF LIGHT MASS FRAGMENTS IN Si -NUCLEUS COLLISIONS AT $14.6 \text{ GeV}/\text{NUCLEON}$

J. Barrette, R. Bellwied, P. Braun-Munzinger, W. E. Cleland, T. Cormier, G. David, J. Dee, O. Dietzsch, E. Duek, M. Fatyga, D. Fox, S. V. Greene, J. R. Hall, T. K. Hemmick, N. Herrmann, R. W. Hogue, B. Hong, K. Jayananda, D. Kraus, B. Shiva Kumar, R. Lacasse, D. Lissauer, W. J. Llope, T. Ludlam, R. Majka, D. Makowiecki, S. K. Mark, S. McCorkle, J. T. Mitchell, M. Muthuswamy, E. O'Brien, V. Polychronakos, C. Pruneau, F. S. Rotondo, J. Sandweiss, N. C. da Silva, J. Simon-Gillo, U. Sonnadara, J. Stachel, H. Takai, E. M. Takagui, T. G. Throwe, L. Waters, C. Winter, K. Wolf, D. Wolfe, C. L. Woody, N. Xu, Y. Zhang,

Z. Zhang, and C. Zou
Nucl. Phys. A544, 423c (July, 1992)

Transverse momentum distributions of light mass beam rapidity fragments ^1H , ^3He , and ^4He in reactions of $^{28}Si + Al, Cu$ and Pb are presented. The widths of the distributions are found to increase with increasing projectile-target overlap. This dependence is not consistent with the observed distributions being associated with the Fermi momentum of the nucleons on the projectile nucleus.

RECENT RESULTS FROM EXPERIMENT 814 AT BROOKHAVEN

J. Barrette, R. Bellwied, P. Braun-Munzinger, W. E. Cleland, T. M. Cormier, G. David, J. Dee, G. E. Diebold, O. Dietzsch, M. Fatyga, D. Fox, J. V. Germani, M. Ghalambor-Dezfuli, S. Gilbert, S. V. Greene, J. R. Hall, T. K. Hemmick, N. Herrmann, B. Hong, G. Ingold, K. Jayananda, D. Kraus, B. Shiva Kumar, R. Lacasse, D. Lissauer, W. J. Llope, T. W. Ludlam, S. McCorkle, R. Majka, S. K. Mark, J. T. Mitchell, M. Muthuswamy, E. O'Brien, V. Polychronakos, C. Pruneau, F. Rotondo, J. Sandweiss, N. C. da Silva, J. Simon-Gillo, U. Sonnadara, J. Stachel, H. Takai, E. M. Takagui, T. G. Th Rowe, C. Winter, G. Wang, L. Waters, K. Wolf, D. Wolfe, C. L. Woody, N. Xu, Y. Zhang, Z. Zhang, and C. Zou

Nucl. Phys. A544, 137c (July, 1992)

Recent results from the E814 collaboration are presented for reactions of 14.6 GeV/nucleon ^{28}Si projectiles with targets of Al, Cu, and Pb. This includes transverse energy distributions over the full solid angle and the distribution of charged particle multiplicity in the forward hemisphere. Furthermore, we present recent results on transverse momentum spectra and rapidity distributions for protons and discuss them in terms of stopping and/or transparency. A fraction of nucleons emerges at beam rapidity, even for the most central collisions. These "punch-through" distributions are shown to yield information on the in-medium nucleon-nucleon cross section. Finally, we discuss antiproton production at 0° as a function of event centrality to shed some light on possible reabsorption.

ENERGY DEPENDENCE OF THE ANALYZING POWER FOR THE $pp \rightarrow \pi^+d$ REACTION IN THE ENERGY REGION 500-800 MeV

H. Y. Yoshida, H. Shimizu, H. Ohnuma, Y. Kobayashi, K. Kobayashi, T. Nakagawa, J. A. Holt, G. Glass, J. C. Hiebert, R. A. Kenefick, S. Nath, L. C. Northcliffe, A. Simon, S. Hiramatsu, Y. Mori, H. Sato, A. Takagi, T. Toyama, A. Ueno, and K. Imai

Nucl. Phys. A541, 443 (May, 1992)

The energy dependence of the analyzing power A_y for the $pp \rightarrow \pi^+d$ reaction was measured during polarized beam acceleration from 500 to 800 MeV, using an internal target inserted into the beam every acceleration cycle. The measurements were made with the pion laboratory angle fixed at 68° and with incident proton energy bins varying from 10 to 30 MeV in width. The statistical accuracy per bin is $\Delta A_y \approx 0.06$.

MECHANISMS OF NON-EQUILIBRIUM LIGHT-PARTICLE EMISSION IN $^{32}S + Ag$ REACTIONS AT 30 A · MeV

R. Wada, M. Gonin, M. Gui, K. Hagel, Y. Lou, D. Utley, J. B. Natowitz, G. Nebbia, D. Fabris, R. Billerey, B. Cheynis, A. Demeyer, D. Drain, D. Guinet, C. Pastor, L. Vagneron, K. Zaid, J. Alarja, A. Giorni, D. Heuer, C. Morand, B. Viano, C. Mazur, C. Ngô, S. Leray, R. Lucas, M. Ribrag, and E. Tomasi

Nucl. Phys. A539, 316 (March, 1992)

Energy spectra of light charged particles ($Z=1,2$), observed at $\theta_{LP} = 5^\circ$ - 150° in coincidence with fragments of $Z = 5$ -14 at $\theta_F = \pm 9^\circ$ are examined. The fragment-energy spectra show two components, one with a projectile-like velocity and another with a much lower velocity. Light particles in coincidence with fragments of projectile-like velocity show a very strong left-right asymmetry in the forward hemisphere. At very forward angles the asymmetry is essentially dominated by a recoil effect of the ejectile emitted from the fragment. The asymmetry at intermediate angles ($27^\circ \leq \theta \leq 60^\circ$)

shows a strong dependence on the charge of the fragments and the asymmetry is similar among those for the composite particles, whereas the asymmetry is much smaller for protons. Light particles in coincidence with the lower-energy component of the fragment spectra show much less asymmetry. For such fragments α -particle energy spectra are reproduced without an intermediate-velocity source of high apparent temperature, whereas this high temperature source is needed for the proton spectra. These facts may indicate that the dominant emission mechanism of the intermediate-velocity protons and α -particles is different. Possible mechanisms for the production of these particles are discussed.

DYNAMICAL AND STATISTICAL PROPERTIES OF HOT NUCLEI

J. B. Natowitz, M. Gonin, K. Hagel, R. Wada, S. Shlomo, X. Bin, M. Gui, Y. Lou, D. Utley, T. Botting, R. K. Choudhury, L. Cooke, B. Hurst, D. O'Kelly, R. P. Schmitt, W. Turmel, H. Utsunomiya, G. Nebbia, D. Fabris, J. A. Ruiz, G. Nardelli, M. Poggi, R. Zanon, G. Viesti, R. H. Burch, F. Gramegna, G. Prete, D. Drain, B. Chambon, B. Cheynis, D. Guinet, X. C. Hu, A. Demeyer, C. Pasteur, A. Giorni, A. Lleres, P. Stassi, B. Viano, A. Menchaca Rocha, M.E. Brandan, and P. Gonthier
Nucl. Phys. A538, 263c (March, 1992)

Properties of medium mass nuclei having excitation energies of 1.5 to 6 MeV/u have been probed in measurements of the multiplicities and energy spectra of emitted particles and fragments. The particle spectra indicate a progressive reduction of both the level density parameter, a , and the emission barriers as the excitation energy is increased. The evolution of the dominant de-excitation modes, observed with increasing excitation energy, is found to be qualitatively consistent with the predictions of statistical models. There is, however, evidence that dynamics may play an important role in fragment emission processes. At energies of 6 MeV/u multifragment emission is an important process. Varying theoretical models predict such multifragment events but differ in their predictions of the probability of such events.

RESPONSE OF THE PARTICIPANT CALORIMETER TO 1.5-6.8 GeV/c ELECTRONS AND HADRONS

D. Fox, J. Simon-Gillo, M. W. Rawool-Sullivan, J. G. Boissevain, W. E. Cleland, A. Gavron, B. V. Jacak, D. Kraus, W. Sondheim, J. P. Sullivan, H. van Hecke, S. Watson, K. L. Wolf, and Z. Zhang
Nucl. Instrum. Methods A317, 474
(February, 1992)

The Participant Calorimeter for Experiment 814 at BNL is a lead-scintillator sampling calorimeter. The response of the calorimeter to beams of e , μ , π and p from 1.56 to 6.8 GeV/c is presented. The design and performance of two gain monitoring systems are described, one system measures the response of single scintillator plates in the calorimeter. The calorimeter electromagnetic energy resolution varies from 24 to 32% $\sqrt{E}$ for different towers. For hadron energies over 5 GeV the $\sigma_h/E = 43 \pm 3\% \sqrt{E}$, and $e/h = 1.02 \pm 0.07$.

DISSOCIATION OF MULTICHARGED CO MOLECULAR IONS PRODUCED IN COLLISIONS WITH 97 MeV Ar^{14+} : DISSOCIATION FRACTIONS AND BRANCHING RATIOS

K. Wohrer, G. Sampoll, R. L. Watson, M. Chabot, O. Heber, and V. Horvat
Phys. Rev. A 46, 3929 (October, 1992)

Data on the production and dissociation of CO^{Q+} molecular ions (where $Q = 1$ through 7) obtained by ion-ion coincidence time-of-flight measurements were analyzed to determine production yields, dissociation fractions, and branching ratios. A detailed comparison of the dissociation fractions for CO^+ and CO^{2+} for several collision systems in the same perturbative regime revealed them to be quite similar, whereas the dissociation fraction for CO^+ produced by valence-electron photoionization is a factor of 1.8 to 3.6 larger. The results for $Q \geq 2$ indicated a preference for dissociation channels leading to symmetric or nearly symmetric charge division. An enhancement of the total ionization yields for $Q > 4$ was observed, and it suggests that electron transfer followed by LMM Auger decay plays an important role in determining the final charges of the dissociation products.

K-SHELL IONIZATION OF INTERMEDIATE-Z ELEMENTS BY 30-MeV/amu H, N, Ne, AND Ar IONS

V. Horvat, G. Sampoll, K. Wohrer, M. Chabot, and R. L. Watson

Phys. Rev. A 46, 2572 (September, 1992)

Cross sections for K x-ray production in solid targets ($Z=13, 22, 26, 29, 32, 40, 42, 46$, and 50) by 30-MeV/amu beams of H, N, Ne, and Ar were measured. The cross sections were determined by recording the spectra of K x-rays with a Si(Li) detector in coincidence with beam particles detected in a microchannel plate assembly. The K-shell-ionization cross sections deduced from these data agree quite well with the predictions of the perturbed-stationary-state theory with energy loss, Coulomb deflection, and relativistic corrections. Detailed analyses of the projectile and target Z dependences of the cross sections were performed. Also, the relative intensities of K x-rays from double K-shell ionization of the higher- Z targets are presented for N, Ne, and Ar projectiles.

DISSOCIATION OF MULTICHARGED CO MOLECULAR IONS PRODUCED IN COLLISIONS WITH 97-MeV Ar^{14+} : TOTAL-KINETIC-ENERGY DISTRIBUTIONS

G. Sampoll, R. L. Watson, O. Heber, V. Horvat, K. Wohrer, and M. Chabot

Phys. Rev. A 45, 2903 (March, 1992)

Transient molecular ions of CO^{q+} (where $q = 2-7$) were produced in single collisions of 97-MeV Ar^{14+} projectile with neutral CO molecules. The resulting dissociation products were identified by coincidence time-of-flight spectroscopy in which the time-of-flight of the first ion to reach the detector and the time difference between the first ion and its partner were recorded event by event. An iterative matrix-transformation procedure was employed to convert the time-difference spectra for the prominent dissociation channels into total-kinetic-energy distributions. Analysis of the total-kinetic-energy distributions and comparisons with the available data for CO^{2+} and CO^{3+} from synchrotron radiation experiments led to the conclusion that ionization by Ar-ion impact populated states having considerably higher excitation energies than those accessed by

photoionization.

SPIN-ROTATION PARAMETERS A AND R FOR π^+p AND πp ELASTIC SCATTERING FROM 427 TO 657 MeV/c

I. Supek, D. B. Barlow, W. J. Briscoe, J. F. Davis, G. J. Kim, D. W. Lane, A. Mokhtari, B. M. K. Nefkens, C. Pillai, M. E. Sadler, C. J. Seftor, M. F. Taragin, and J. A. Wightman

Phys. Rev. D 47, 1762 (March, 1993)

The spin-rotation parameters A and R and the related spin-rotation angle β have been measured for π^+p and πp elastic scattering using protons polarized in the scattering plane. The pion-beam momenta are 427, 471, 547, 625, and 657 MeV/c and the angular range is $-0.9 \leq \cos\theta_{\text{c.m.}} \leq 0.3$. The scattered pion and recoil proton were detected in coincidence, using a scintillator hodoscope for the pions, and the Large Acceptance Spectrometer combined with the JANUS polarimeter for the recoil protons. The results are compared with the four recent πN partial wave analyses (PWA's). Our data show that the major features of these PWA's are correct. The A and R measurements complete our program of pion-nucleon experiments, providing full data sets at three of the above beam momenta. Such sets can be used to test the constraints in the PWA's or to obtain a model-independent set of πN scattering amplitudes.

NEUTRON-PROTON ELASTIC SCATTERING SPIN-SPIN CORRELATION PARAMETER MEASUREMENTS BETWEEN 500 AND 800 MeV. II. C_{SS} AND C_{LS} AT FORWARD c.m. ANGLES

T. Shima, D. Hill, K. F. Johnson, H. Shimizu, H. Spinka, R. Stanek, D. Underwood, A. Yokosawa, G. Glass, J. C. Hiebert, R. A. Kenefick, S. Nath, L. C. Northcliffe, G. R. Burleson, R. W. Garnett, J. A. Faucett, M. W. Rawool-Sullivan, R. Damjanovich, J. J. Jarmer, R. H. Jeppesen, and G. E. Tripard

Phys. Rev. D 47, 29 (January, 1993)

Results are presented for the spin-spin correlation parameters C_{SS} and C_{LS} for free np elastic scattering at neutron beam kinetic energies of 484, 634, 720, and 788 MeV and c.m. angles between 25° and 80° . The measurements were performed with a polarized neutron beam and a polarized proton target. These

are the first measurements of this type to be reported in the forward angular region with a free polarized neutron beam. The observables C_{SS} and C_{LS} are both small at all energies, except for C_{LS} at 788 MeV, which is larger than phase-shift analysis predictions by more than one standard deviation for most of the measured points.

NEUTRON-PROTON ELASTIC SCATTERING
SPIN-SPIN CORRELATION PARAMETER
MEASUREMENTS BETWEEN 500 AND 800
MeV. I. C_{LS} AND C_{LL} AT BACKWARD c.m.
ANGLES

W. R. Ditzler, D. Hill, J. Hoftiezer, K. F. Johnson,
D. Lopiano, T. Shima, H. Shimizu, H. Spinka, R.
Stanek, D. Underwood, R. G. Wagner, A.
Yokosawa, G. R. Burleson, J. A. Faucett, C. A.
Fontenla, R. W. Garnett, C. Luchini, M. W.
Rawool-Sullivan, T. S. Bhatia, G. Glass, J. C.
Hiebert, R. A. Kenefick, S. Nath, L. C.
Northcliffe, R. Damjanovich, J. J. Jarmer,
J. Vaninetti, R. H. Jeppesen, and G. E. Tripard
Phys. Rev. D **46**, 2792 (October, 1992)

Final results are presented for the spin-spin correlation parameters C_{LS} and C_{LL} for np elastic scattering with a polarized neutron beam incident on a polarized proton target. The beam kinetic energies are 484, 634, and 788 MeV, and the c.m. angular range is 80° - 180° . These data will contribute significantly to the determination of the isospin-0 amplitudes in the energy range from 500 to 800 MeV.

SOME ASPECTS OF PION PRODUCTION IN
HEAVY ION COLLISIONS

M. I. Gorenstein, S. N. Yang, and C. M. Ko
Chinese Journal of Physics **30**, 543 (August, 1992)

Pion production in high energy heavy-ion collisions is studied in the hydrochemical model in which chemical reactions are explicitly considered in the expansion stage of the hadronic phase. We find that chemical equilibrium is not established among the hadronic particles. This results in a large value for pion chemical potential at the thermal freeze out, leading to an enhanced production of low energy pions. By introducing the notion of electrical chemical potential to account for the charge conservation, we further find that the excess of low energy π^+ is less than that of π^- . We also find a plateau-like structure in the incident energy dependence of the pion multiplicity as a result of the formation of the quark-hadron mixed phase in the initial stage of the collision.

ABSTRACTS OF PAPERS SUBMITTED

April, 1992 - March, 1993

SEEING THE QCD PHASE TRANSITION WITH THE PHI MESON

M. Asakawa and C. M. Ko
Phys. Rev. Lett. (Submitted, 1993)

A double phi peak structure in the dilepton invariant mass spectrum from ultrarelativistic heavy ion collisions is proposed as signal for the phase transition from the quark-gluon plasma to the hadronic matter. The low mass phi peak results from the reduced phi meson mass in hot hadronic matter because of the partial restoration of the chiral symmetry and the long duration time of the phase transition. Since the low mass phi mesons decay into dileptons mainly during the phase transition, the measurement of its transverse momentum distribution offers thus a viable means for determining the transition temperature between the quark-gluon plasma and the hadronic matter.

np-ELASTIC ANALYZING POWER A_{NO} AND SPIN TRANSFER K_{NN}

M. W. McNaughton, K. Johnston, D. Swenson, D. Tupa, R. York, D. A. Ambrose, P. Coffey, K. H. McNaughton, P. J. Riley, G. Glass, J. C. Hiebert, R. H. Jeppesen, H. Spinka, I. Supek, G. E. Tripard, and H. L. Woolverton
Phys. Rev. C (February, 1993)

We have measured the analyzing power A_{NO} and the spin transfer K_{NN} for np elastic scattering from about 60° to 170° c.m. at 485, 635, and 788 MeV. The new data clarify previous discrepancies and complete the first order determination of nucleon-nucleon elastic scattering at these energies.

DEUTERON ELASTIC SCATTERING AT 100 AND 120 MeV

A. C. Betker, C. A. Gagliardi, D. R. Semon, R. E. Tribble, H. M. Xu, and A. F. Zaruba
Phys. Rev. C (March, 1993)

Deuteron elastic scattering cross sections have been measured at 100 and 120 MeV on C, ^{58}Ni , and ^{208}Pb . Optical model potentials have been extracted and compared to deuteron global optical model potentials.

FORMATION AND DECAY OF TOROIDAL AND BUBBLE NUCLEI AND THE NUCLEAR EQUATION OF STATE

H. M. Xu, J. B. Natowitz, C. A. Gagliardi, R. E. Tribble, C. Y. Wong, and W. G. Lynch
Phys. Rev. C (in press)

Multifragmentation, following the formation of toroidal and bubble nuclei is observed with an improved BUU model for central $^{92}\text{Mo} + ^{92}\text{Mo}$ collisions. With a stiff equation of state, simultaneous explosion into several intermediate mass fragments (IMF) in a ring-like manner occurs due to the formation of metastable toroidal nuclei. In contrast, with a soft equation of state, simultaneous explosion into several IMF's in a volume-like manner occurs due to the formation of metastable bubble nuclei. Experimental signatures for the formation of these exotic shapes are discussed.

NUCLEAR STRUCTURE STUDY OF THE ODD-A Tc ISOTOPES WITHIN THE NEUTRON-PROTON INTERACTING BOSON- FERMION MODEL

H. Dejbakhsh and S. Shlomo
Phys. Rev. C (in press)

We have investigated the odd-A Tc isotopes in the mass 100 region within the neutron-proton interacting boson-fermion model (IBFM-2). The calculation is based on the validity of the $Z=38$ subshell closure. The results for the energy spectra and electromagnetic transitions are compared with experimental data and with results from other calculations which considered $Z=50$ as a valid closed shell for Tc isotopes.

MEDIUM EFFECTS ON SUBTHRESHOLD KAON PRODUCTION FROM HEAVY-ION COLLISIONS

Y. M. Zheng, X. S. Fang, and C. M. Ko
Phys. Rev. C (Submitted, 1993)

The relativistic transport model, in which the nucleon effective mass is connected to the scalar field while its energy is shifted by the vector potential, is extended to include the kaon degree of freedom. We further take into account the density dependence of the kaon effective mass in nuclear matter due to the explicit chiral symmetry breaking. For kaon propagation in nuclear matter, we also include the repulsive vector potential due to nucleons. The effect of reduced kaon mass on kaon production from the baryon-baryon interaction is evaluated in the one-pion-exchange model. We find that the reduced kaon mass in dense matter leads to an enhanced kaon yield in heavy-ion collisions at about 1 GeV/nucleon that is below the threshold for kaon production from nucleon-nucleon interaction in free space. We have also included explicitly the kaon rescattering from nucleons. Both kaon rescattering and the repulsive vector potential affect significantly the final kaon kinetic energy spectra. The calculated kaon energy spectra with the improved relativistic transport model agree reasonably with the preliminary data from the SIS at GSI.

MEDIUM EFFECTS ON KAON AND ANTIKAON SPECTRA IN HEAVY-ION COLLISIONS

X. S. Fang, C. M. Ko, G. E. Brown and V. Koch
Phys. Rev. C (Submitted, 1993)

In the linear chiral perturbation theory, both kaon and antikaon masses decrease in dense matter. There is also a repulsive vector potential for the kaon and

an attractive one for the antikaon. With these effects included in the relativistic transport model, it is found that the slope parameter of the kaon kinetic energy distribution is larger than that of the antikaon. This is consistent with the experimental data from heavy-ion collisions in the Alternating Gradient Synchrotron experiments at Brookhaven.

MEDIUM EFFECTS ON THE RHO MESON

M. Asakawa and C. M. Ko
Phys. Rev. C (Submitted, 1993)

The property of a rho meson in dense matter is studied using the QCD sum rule. The spectral function appearing on the hadronic side of the sum rule is evaluated in the vector dominance model that takes into account the interaction between the rho meson and the pion. Including pion modification by the delta-hole polarization in the nuclear medium, we find that as the nuclear density increases the rho meson peak in the spectral function shifts to smaller invariant masses and its width becomes smaller. We discuss the possibility of studying the rho meson property in dense matter via the dilepton invariant mass spectrum from heavy-ion collisions.

ENERGY DEPENDENT MEASUREMENTS OF THE p-p ELASTIC ANALYZING POWER AND NARROW DIBARYON RESONANCES

Y. Kobayashi, K. Kobayashi, T. Nakagawa, H. Shimizu, H. Y. Yoshida, H. Ohnuma, J. A. Holt, G. Glass, J. C. Hiebert, R. A. Kenefick, S. Nath, L. C. Northcliffe, A. J. Simon, S. Hiramatsu, Y. Mori, H. Sato, A. Takagi, T. Toyama, A. Ueno, and K. Imai
Nucl. Phys. A (Submitted, 1992)

The energy dependence of the p-p elastic analyzing power has been measured using an internal target during polarized beam acceleration. The data were obtained in incident-energy steps varying from 4 to 17 MeV over an energy range from 0.5 to 2.0 GeV. The statistical uncertainty of the analyzing power is typically less than 0.01. A narrow structure is observed around 2.17 GeV in two proton invariant mass distribution. A possible explanation for the structure with narrow resonances is discussed.

PHI MESON MASS IN HOT AND DENSE MATTER

M. Asakawa and C. M. Ko
Nucl. Phys. A (Submitted, 1993)

The phi meson mass in hot and dense nuclear matter is studied in the QCD sum rules method. We find that it decreases substantially as a result of the abundant number of strange particles in the matter.

QCD SUM RULES FOR RHO MESON IN DENSE MATTER

M. Asakawa and C. M. Ko
Nucl. Phys. A (in press)

Using the QCD sum rules, we study the property of a rho meson in dense hadronic matter. Instead of the simple rho meson pole approximation for the rho meson spectral function at low momenta, we evaluate it using the vector dominance model that takes into account the interaction between rho meson and pion. Including pion modification by the delta-hole polarization in the nuclear medium, we find that as the nuclear density increases the rho meson peak in the spectral function shifts to smaller invariant masses. We discuss the possibility of studying the rho meson property in dense matter via the dilepton invariant mass spectrum from heavy ion collisions.

RESCATTERING EFFECTS ON KAON ENERGY SPECTRA IN HEAVY-ION COLLISIONS

X. S. Fang, C. M. Ko, and Y. M. Zheng
Nucl. Phys. A (in press)

Kaon production from heavy ion collisions at energies that are below the threshold for its production in free space is studied in the relativistic Vlasov-Uehling-Uhlenbeck model. Because of the small production probability, kaon production in baryon-baryon reactions is treated perturbatively. The rescattering of the kaon by nucleons is, however,

included in the calculation. It is found that kaons undergo substantial rescatterings as they are mostly produced in high density region. This leads to significant effects on kaon final kinetic energy spectra.

DYNAMICAL PAIR PRODUCTION AND INDUCED CURRENT IN BOOST-INVARIANT FLUX-TUBE MODEL

M. Asakawa
Phys. Rev. D (Submitted, 1992)

We calculate the current induced by boost-invariant external flux-tube field to understand pair production in dynamical situations. By solving one particle Dirac equation under the classical boost-invariant external field, we show that if the fermion is massless no current is observed in the flux-tube. The result is confirmed by calculating also the linear response of the vacuum. We also consider the pair production classically when the flux-tube is still invariant under the Lorentz boost in the longitudinal direction but expanding transversely. It is suggested that in the case with transverse expansion the phenomenological longitudinal momentum dependence of the pair production which has been used in the literature is understood naturally.

RHO MESON SPECTRAL FUNCTION IN DENSE MATTER

C. M. Ko
Phys. Rep. (in press)

The spectral function of a rho meson at rest in dense hadronic matter is studied in the vector dominance model by including both the effect of the delta-hole polarization on pion and the scaling in-medium hadron masses of Brown and Rho. It is found that as the nuclear density increases the rho meson peak moves to smaller invariant masses with diminishing strength. Also, a low mass peak around three times the pion mass appears and shifts down with increasing density. The change of the rho meson property in dense matter can be investigated via the dilepton invariant mass spectrum from heavy-ion collisions.

IONIZATION OF NOBLE GAS ATOMS BY ALPHA PARTICLES AND FISSION FRAGMENTS FROM THE DECAY OF ^{252}Cf

B. M. Hill, R. L. Watson, K. Wohrer, B. B.
Bandong, G. Sampoll, and V. Horvat
(in press)

Charge state distributions of He, Ne, Ar, Kr, and Xe ions produced in single collisions with alpha particles and fission fragments from the decay of ^{252}Cf have been measured using time-of-flight spectroscopy. The measurements reveal that the maximum number of electrons removed in a fission fragment collision ranges from 8 in the case of Ne to 20 in the case of Xe. Recoil-ion production cross sections have been determined for the resolvable ionic charge states and compared with the predictions of a model based upon the independent electron approximation.

NUCLEAR EFFECTS IN DILEPTON AND QUARKONIUM PRODUCTION

S. V. Akulinichev
(February, 1993)

The dilepton, J/ψ and T production in nuclei by fast protons and pions is discussed. A new scenario is suggested: the initial state interactions are described by inelastic scattering (absorption) of constituent quarks, whereas for the final state interactions in quarkonium production we adopt the "color transparency" model. For the dilepton production by protons the contribution of excess pions is important. The available data are qualitatively described.

STATISTICAL AND DYNAMICAL ASPECTS OF HOT NUCLEUS DE-EXCITATION

M. Gui, K. Hagel, J. Li, Y. Lou, J. B. Natowitz, R.
Wada, D. Utley, B. Xiao
(January, 1993)

Proceedings of Predeal International Summer
School

Recent experiments designed to explore fragment emission dynamics, time scales for fragment emission from highly excited nuclei, and multifragment emission processes are summarized. Reactions

studied include 18.5 AMeV $^{136}\text{Xe} + ^{48}\text{Ti}$, 30 AMeV $^{32}\text{S} + \text{Ag}$ and 35 AMeV $^{40}\text{Ca} + ^{40}\text{Ca}$. Nuclei with excitation energies of 3-6 MeV/u are produced in these reactions.

TWO THEOREMS ON THE KERNEL OF FADDEEV EQUATIONS FOR SCATTERING OF THREE CHARGED PARTICLES AND SOME APPLICATIONS

D. M. Latypov and M. K. Mukhamedzhanov
J. Math. Phys. (Submitted, 1993)

The operator T^*G_0 which represents the singular part of kernel of Faddeev equations for the scattering of charged particles above breakup threshold is studied. The operator is considered in two classes of functions. The functions from the first class have on-shell limit and the functions from the second class have an on-shell singularity of a type $(z-P^2)^{i\alpha}$, $\alpha \in \mathbb{R}$. In both classes the most singular part of T^*G_0 is found to be proportional to a delta function. In order for Faddeev equations to have a solution in the second class, α is shown to be equal to the sum of Sommerfeld parameters of all two-body subsystems.

ON THE COULOMB SINGULAR KERNEL OF LIPPMAN-SCHWINGER TYPE EQUATION

D. M. Latypov and A. M. Mukhamedzhanov
J. Math. Phys. (Submitted, 1993)

Lippman-Schwinger type equation with Coulomb singular kernel is considered. It is shown that all its solutions are singular on the energy shell, $k^2/2\mu = E$. In order for this equation to have a solution with a singularity of the type $(E-k^2/2\mu + i\epsilon)^{i\alpha}$, α is shown to be equal to the Coulomb parameter η . The Coulomb singular kernel in the given class of functions is found to split into a δ -function and a kernel which smoothes the singularity.

APPENDIX

TALKS PRESENTED
April 1992 - March 1993

Competing De-Excitation Modes in Hot Nuclei, J. B. Natowitz, Invited Talk, Catania Workshop on Heavy Ion Reactions, Catania, Italy (May, 1992).

Rho Meson Spectral Function in Dense Matter, C. M. Ko, Invited Talk, Conference on Realistic Nuclear Structure, Stony Brook, New York (May, 1992).

Hadrons in Dense Matter, M. Asakawa, C. M. Ko, P. Lévai, International Workshop on QCD Vacuum, Paris, France (June, 1992).

Performance of the Texas A&M ECRIS, G. Mouchaty, R. C. Rogers, P. Smelser, D. P. May, 13th International Conference on Cyclotrons and their Applications, Vancouver, Canada (June, 1992).

Design of a Beam Buncher Using a Half-Cosine Driving Function, R. C. Rogers, 13th International Conference on Cyclotrons and their Applications, Vancouver, Canada (June, 1992).

Effect of the Main Coil Position on the Accelerated Beam of the K500 Cyclotron, D. P. May and G. Mouchaty, 13th International Conference on Cyclotrons and their Applications, Vancouver, Canada (June, 1992).

Results from the Deflector Test Stand at Texas A&M University, D. May, G. Derrig, W. Dewees, P. Smelser, D. Tran, R. C. Rogers, 13th International Conference on Cyclotrons and their Applications, Vancouver, Canada (June, 1992).

Probing Dense Hadronic Matter in Heavy Ion Collisions, C. M. Ko, Invited Talk, International Workshop on Intermediate and High Energy Nuclear Physics, Beijing, China (August, 1992).

Statistical and Dynamical Aspects of Hot Nucleus De-Excitation, J. B. Natowitz, Invited Talk, International Predeal School on Nuclear Physics, Predeal, Romania (August, 1992).

Dynamical and Statistical IMF Emission in Heavy Ion Reactions Near the Fermi Energy, R. Wada, K. Hagel, H. L. Johnston, J. Li, Y. Lou, D. Utley, B. Xiao, J. B. Natowitz, Fall Meeting of the Division of Nuclear Physics, Santa Fe, New Mexico, (October, 1992), Bulletin of the American Physical Society 37 No. 5, pg. 1262 (1992).

Exaporation Residue Production in Reactions with 35 and 40 AMeV ^{40}Ar , D. Utley, Y. Lou, B. Xiao, M. Gui, J. Li, R. Wada, K. Hagel, J. B. Natowitz, Fall Meeting of the Division of Nuclear Physics, Santa Fe, New Mexico (October, 1992), Bulletin of the American Physical Society 37 No. 5, pg. 1262 (1992).

Fission-Like Processes in the Reaction $^{63}\text{Cu} + ^{100}\text{Mo}$ at 10, 17 and 25 MeV/u, Y. Lou, T. Botting, L. Cooke, M. Gonin, M. Gui, K. Hagel, B. Hurst, G. Mouchaty, J. Natowitz, D. O'Kelly, R. P. Schmitt, W. Turnel, D. Utley, R. Wada, M. E. Brandan, A. Menchaca-Rocha, B. Burch, D. Fabris, G. Nebbia, F. Gramegna, M. Poggi, G. Prete, J. Ruiz, G. Viesti, Fall Meeting of the Division of Nuclear Physics, Santa Fe, New Mexico (October, 1992), Bulletin of the American Physical Society 37 No. 5, pg. 1299 (1992).

Hot Nuclei Produced in the $^{40}\text{Ca} + ^{40}\text{Ca}$ Reaction at 35 MeV/u, K. Hagel, M. Gonin, R. Wada, J. B. Natowitz, B. H. Sa, Y. Lou, M. Gui, D. Utley, G. Nebbia, D. Fabris, G. Prete, J. Ruiz, D. Drain, B. Chambon, B. Cheynis, D. Guinet, S. C. Hu, A. Demeyer, C. Pastor, A. Giorni, A. Lleres, P. Stassi, J. B. Viano, P. Gonthier, Fall Meeting of the Division of Nuclear Physics, Santa Fe, New Mexico (October, 1992), Bulletin of the American Physical Society 37 No. 5, pg. 1262 (1992).

The Mass Asymmetry Dependence of Scission Times in the Reactions of $18.5 \text{ A MeV } ^{136}\text{Xe} + ^{48}\text{Ti}$, M. Gui, K. Hagel, Y. Lou, J. B. Natowitz, D. Utley, R. Wada, B. Xiao, G. Enders, W. Kühn, V. Metag, R. Novotny, O. Schwalb, R. Charity, R. Freifelder, A. Gobbi, W. Henning, K. D. Hildenbrand, R. Mayer, R. S. Simon, J. Wessels, G. Casini, A. Olmi, A. A. Stefanini, Fall Meeting of the Division of Nuclear Physics, Santa Fe, New Mexico (October, 1992), Bulletin of the American Physical Society 37 No. 5, pg. 1261 (1992).

Phi Meson in Hot Dense Matter, M. Asakawa and C. M. Ko, Bulletin of the American Physical Society, Santa Fe, New Mexico (October, 1992).

Rescattering Effects on Kaon Spectrum in Heavy Ion Collisions, X. S. Fang and C. M. Ko, Bulletin of the American Physical Society, Santa Fe, New Mexico (October, 1992).

The M_T -Scaling in the Dilepton Spectrum as a Signature for the Quark-Gluon Plasma, M. Asakawa and C. M. Ko, International Workshop XXI on Gross Properties of Nuclei and Nuclear Excitations, Hirschegg, Austria (January, 1993).

Particle Production and Propagation in Dense Matter, C. M. Ko, Invited Talk, Workshop on Heavy-Ion Physics at the AGS, Boston, Massachusetts (January, 1993).

Kaon Production and Propagation in Dense Matter Formed in Heavy Ion Collisions at Subthreshold Energies, C. M. Ko, X. S. Fang, Y. M. Zheng, International Workshop XXI on Gross Properties of Nuclei and Nuclear Excitations, Hirschegg, Austria (January, 1993).

Medium Effects on Subthreshold Kaon Production in Heavy Ion Collisions, X. S. Fang, C. M. Ko, Y. M. Zheng, Ninth Winter Workshop on Nuclear Dynamics, Key West, Florida (February, 1993).

Rho Meson in Dense Matter, C. M. Ko and M. Asakawa, Ninth Winter Workshop on Nuclear Dynamics, Key West, Florida (February, 1993).

CONFERENCE PROCEEDINGS
April 1, 1992 - March 31, 1993

Rho Meson Spectral Function in Dense Matter, C. M. Ko, Conference on Realistic Nuclear Structure, Stony Brook, New York (May, 1992) (in press).

Performance of the Texas A&M ECRIS, G. Mouchaty, R. C. Rogers, P. Smelser, D. P. May, 13th International Conference on Cyclotrons and their Applications, Vancouver, Canada (June, 1992), p. 369.

Design of a Beam Buncher Using a Half-Cosine Driving Function, R. C. Rogers, 13th International Conference on Cyclotrons and their Applications, Vancouver, Canada (June, 1992), p. 629.

Effect of the Main Coil Position on the Accelerated Beam of the K500 Cyclotron, D. P. May and G. Mouchaty, 13th International Conference on Cyclotrons and their Applications, Vancouver, Canada (June, 1992), p. 439.

Results from the Deflector Test Stand at Texas A&M University, D. May, G. Derrig, W. Dewees, P. Smelser, D. Tran, R. C. Rogers, 13th International Conference on Cyclotrons and their Applications, Vancouver, Canada (June, 1992), p. 602.

Hadrons in Dense Matter, M. Asakawa, C. M. Ko, P. Lévai, Proceedings of the International Workshop on QCD Vacuum, Paris, France (June, 1992), p. 298.

Probing Dense Hadronic Matter in Heavy Ion Collisions, C. M. Ko, International Workshop on Intermediate and High Energy Nuclear Physics, Beijing, China (August, 1992).

Particle Production and Propagation in Dense Matter, C. M. Ko, Workshop on Heavy-Ion Physics at the AGS, Boston, Massachusetts (January, 1993) (in press).

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The M_π -Scaling in the Dilepton Spectrum as a Signature for the Quark-Gluon Plasma, M. Asakawa and C. M. Ko, Proceedings of the International Workshop XXI on Gross Properties of Nuclei and Nuclear Excitations, Hirschegg, Austria (January, 1993) (in press).

Rho Meson in Dense Matter, C. M. Ko and M. Asakawa, Ninth Winter Workshop on Nuclear Dynamics, Key West, Florida (February, 1993) World Scientific (in press).

Medium Effects on Subthreshold Kaon Production in Heavy Ion Collisions, X. S. Fang, C. M. Ko, Y. M. Zheng, Proceedings of the Ninth Winter Workshop on Nuclear Dynamics, Key West, Florida (February, 1993) World Scientific (in press).

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 Anastasia Zaruba²⁴

¹From 1-1-93

²From 8-24-92 - 12-31-92

³From 2-1-93

⁴From 6-1-92

⁵From 5-1-92

⁶From 7-1-92

⁷From 12-1-92

⁸Through 4-30-92

⁹Through 8-31-92

¹⁰From 9-7-92

¹¹Through 2-28-93

¹²From 3-1-93

¹³From 6-1-92 - 2-28-93

¹⁴Through 12-31-92

¹⁵Through 5-31-92

¹⁶Through 5-31-92

¹⁷Through 5-31-92

¹⁸From 1-1-93

¹⁹From 6-4-92

²⁰From 7-1-92

²¹From 6-1-92

²²From 2-1-93

²³From 12-1-92 - 1-31-93

²⁴Through 12-31-92

INSTITUTE COLLOQUIUM SERIES

April 2	Jeremy Brown, Princeton University	Proton Induced Pion Production Near Threshold
April 7	John Boger, State University of New York at Stony Brook	Asymmetric Fission Barriers: A Comparison of Derived Versus Predicted Barriers
April 13	Sherry Yennello, Michigan State University	Understanding Nuclear Fragmentation Reaction Mechanisms
April 14	Shoji Nagamiya, Columbia University, New York	Nuclear Matter as an Assembly of Quarks- Experimental Challenge with Heavy Ion Beams
May 5	Umesh Garg, University of Notre Dame	From Single-Particle to Superdeformed: A Multitude of Shapes in the Hg Nuclei
May 21	Rick Casten, Brookhaven National Laboratory	Valence Correlation Schemes and Collectivity in Nuclei
June 9	Ben Zeidman, Argonne National Laboratory and Hampton University	A Brief Overview of the Startup CEBAF Experimental Program
July 2	Michael Murray, Los Alamos National Laboratory	Particle Spectra and Interferometry Results in Relativistic Heavy Ion Experiments
July 16	Arturo Gomez, Nuclear Science Institute, Mexico	RPA Calculations of the Nuclear Response Function in the Continuum
August 20	T. Udagawa, University of Texas at Austin	Decay of the Delta Excited in Nuclei
August 25	R. Eramzhyan, Institute for Nuclear Research, Moscow, Russia	Photofragmentation of ${}^6\text{Li}$ and ${}^7\text{Li}$
September 11	R. Eramzhyan, Institute for Nuclear Research, Moscow, Russia	Induced Pseudo-Scalar Weak Coupling and Spin Multipole Excitation in Nuclei

September 25	D. Kella, Weizmann Institute of Science, Israel	Probing the First Microsecond After the Small Bang-Coulomb Explosion Imaging at the Weizmann Institute
October 5	R. Eramzhyan, Institute for Nuclear Research, Moscow, Russia	Decay of Giant Dipole Resonance in the sd Shell Nuclei
October 19	M. Gonin, Brookhaven National Laboratory	Hadron Production in Si + A and Au + Au at AGS Energies
October 20	Linwood Lee, State University of New York at Stony Brook	Near-Barrier Heavy-Ion Transfer Reactions
October 23	G. Viesti, University of Padova, Italy	Level Density Studies in Highly Excited Nuclei with A=40-160
October 30	Guoqiang Li, University of Idaho, Moscow	Theoretical Description of Particle Production in Nucleus-Nucleus Collisions
November 11	Claude Lyneis, Cyclotron Laboratory, Berkeley	Advanced ECR Source for the Cyclotron
November 13	C. Y. Wong, Oak Ridge National Laboratory	The Decay of Toroidal and Bubble Nuclei
November 17	Don Shapira, Oak Ridge National Laboratory	Fusion and Transfer at Sub- and Near-Barrier Energies
November 24	M. Rajasekaran, University of Madras, India	Particle Emission from Excited Fused Compounds at High Spins
December 1	Jill Marques, University of Sao Paulo, Brazil	Symmetrical Representation of the Transition Matrix
December 8	Vladimir Zelevinsky, Institute for Nuclear Physics, Novosibirsk, Russia	Regular and Chaotic Features of Many Body Dynamics

January 12	Yoram Alhassid, Yale University	Hot Nuclei - Theory and Phenomena
January 28	Li Xiong, State University of New York at Stony Brook	Photon and Dilepton Production at RHIC's Energies
February 16	S. V. Akulinichev, Institute for Nuclear Research, Moscow, Russia	Nuclear Effects in Dilepton and Quarkonium Production
February 23	David J. Vieira, Los Alamos National Laboratory	Studies of Exotic Nuclei at LAMPF and GSI
March 12	S. Pratt, Michigan State University	Hadronic Microscopes for Intermediate-Energy Heavy-Ion Collisions
March 26	Chungsik Song, University of Minnesota	Effective Field Theory of Hadrons at Finite Temperature
March 29	X.-Q. Xie, Lawrence Berkeley Laboratory	Physics of the ECR Source
March 30	Xin-Nian Wang, Lawrence Berkeley Laboratory	Parton Dynamics in Ultrarelativistic Heavy-Ion Collisions

INTERNAL INSTITUTE SEMINARS

December 10	Donna O'Kelly, Texas A&M University	Electromagnetic Dissociation of Nuclei
February 8	Angie Betker, Texas A&M University	Initial Performance of the Proton Spectrometer
March 2	Hongming Xu, Texas A&M University	Disappearance of Fusion, Flow and Rotation in Heavy Ion Collisions

END

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5/9/94